TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 364

TESTS IN THE VARIABLE DENSITY WIND TUNNEL TO INVESTIGATE THE EFFECTS OF SCALE AND TURBULENCE ON AIRFOIL CHARACTERISTICS

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Summary

The effects of scale and turbulence on the lift and drag of five airfoils, the N.A.C.A. 0006, the N.A.C.A. 0021, the Clark Y, the U.S.A. 35-A, and the U.S.N. P.S.6, have been investigated in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. Tests were made over a wide scale range for only two different conditions of turbulence.

Because of the limited scope of the tests, no general conclusions have been drawn, but it is indicated that increasing either turbulence or scale eliminates the discontinuities in the lift curves for thick airfoils, and that the effects of increased turbulence on the profile drag of airfoils tend to become of small importance at very high Reynolds Numbers. It is further indicated that the effects of large scale changes on the aerodynamic characteristics of airfoils are of greater importance than the effects of large turbulence changes.

Introduction

The inception of extensive wind tunnel testing of airfoils was marked by the early discovery of serious discrepancies in the results from different tunnels. Tests on geometrically similar airfoils will, even now, give different results when the tests are made in different wind tunnels. The magnitude of the discrepancies is often so great that the minimum drag values for one airfoil tested in two different wind tunnels differ more than the corresponding values for two different airfoils tested in the same wind tunnel.

Generally speaking, the causes for discrepancies fall under three major classifications. These are: first, technique and care employed in conducting the tests; second, Reynolds Number or scale differences between different tests; and third, differences in the turbulence of the air streams of different wind tunnels. At the present time, however, because of improvements in technique, the first of these three has been largely eliminated. Further, the effects of scale can now be estimated from data obtained in the Variable Density Wind Tunnel. The remaining cause for discrepancy, variations in wind tunnel turbulence, has not been extensively investigated, particularly in relation to airfoil characteristics, so that no reliable estimate of its effect can be made.

Investigation of the effects of turbulence on airfoil characteristics was not actively pursued in the past, because it was believed that these effects were small. However, as investigations on airship forms have progressed it has become evident that airfoils, too, may show marked turbulence effects. In fact, a comparison of test results from different wind tunnels has indicated the existence of important differences that may be attributed to differences in turbulence.

Some differences in the results of tests made in the original and in the present form of the Variable Density Wind Tunnel, which may be attributed to turbulence, have appeared; and the present investigation was undertaken to provide information that would help to explain these differences. It was further believed that the information would assist in the interpretation of the results of tests made under approximately similar conditions in different wind tunnels.

The tests were made in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics in conjunction with preparations for an extensive and systematic series of airfoil tests. Lift and drag measurements were made on several airfoils over a large range of Reynolds Numbers for two conditions of turbulence. Five airfoils, the N.A.C.A. 0006, the N.A.C.A. 0021, the Clark Y, the U.S.A. 35-A, and the U.S.N. P.S.6, were included in the investigation. The U.S.A. 35-A airfoil was chosen as an example of airfoils that have shown unfavorable scale effects on maximum lift. The selection of

the U.S.N. P.S.6 airfoil was made for a similar reason, and, in addition, it was chosen as an example of airfoils that low scale tests have shown to have a sudden break in the lift curve at maximum lift. The Clark Y was chosen as an example of airfoils that have shown favorable scale effects on maximum lift. The N.A.C.A. 0006 airfoil (a symmetrical airfoil, 6 per cent thick) was chosen for two reasons; first, it shows normally no scale effect on maximum lift, and second, its symmetry and small thickness connote small pressure drag and small pressure gradients. Accordingly, it is permissible to compare its minimum profile drag values with the drag values for a flat plate placed parallel to the air flow. The N.A.C.A. 0021 airfoil (a symmetrical airfoil, 21 per cent thick) was chosen as an example of a thick symmetrical section.

Apparatus and Method

A detailed description of the Variable Density Wind Tunnel, in which these tests were performed, is given in Reference 1. The description there given is, however, of the original tunnel. In its present form this equipment differs from the original in several respects. The changes in the tunnel may best be noted by comparing the diagrammatic cross section given in this report (Fig. 1) with the corresponding figure of Reference 1.

The models were of 5-inch chord and 30-inch span and were constructed of duralumin. The surfaces of all models except the

U.S.N. P.S.6 were polished. All models were mounted on rigid supports projecting from the balance cradle through the bottom of the tunnel. In order to minimize the effects due to support drag, the struts were partially covered with fairings secured to the tunnel. The effects of the supports were determined, as usual, by measuring the air forces on the struts with a model mounted in the normal position at zero degress angle of attack but independent of the balance.

Artificial turbulence was introduced by means of a coarse screen, 58 inches in diameter, placed 17 inches ahead of the model. The screen consisted of round-edge steel strips, 5/16 inch wide and 1/16 inch thick. The strips were laid at right angles, 1-1/2 inches on centers, and were woven so as to produce a square mesh lattice having 1-3/16-inch openings. To check the efficacy of the screen as a producer of turbulence, the critical Reynolds Numbers with and without the screen installed were determined with a 20-cm sphere.

Tests were made on each airfoil for two conditions of turbulence, and (except for the tests on the U.S.N. P.S.6 airfoil) were extended over the range of the Reynolds Number included between that obtained in the usual Atmospheric Wind Tunnel and 3,400,000. Data for complete lift curves were obtained for the Clark Y and the N.A.C.A. 0021 airfoils and data for complete drag curves for the Clark Y were obtained simultaneously with the lift measurements. Only the minimum drags

of the N.A.C.A. 0021 were measured. The measurements on the U.S.N. P.S.6 were limited to complete lift-curve determinations for three values of the Reynolds Number. On the N.A.C.A. 0006 airfoil, tests to determine only the maximum lifts and the minimum drags were made; and on the U.S.A. 35-A airfoil, measurements of the maximum lifts only were made.

Over most of the scale range covered corresponding Reynolds Numbers could be chosen for the tests made with and without the screen installed. The screen materially lowered the velocity of the tunnel air stream, but the effect of the lowered velocity was counteracted by an increase in the air density. It was impossible, however, to obtain values of the Reynolds Number as high as 3,400,000 when the screen was installed, because the increased density required to offset the lowered velocity would necessitate increasing the air pressure beyond the safe limit for the tank which encloses the tunnel.

The dynamic pressure was determined by means of a micromanometer connected to calibrated static pressure orifices. The orifice calibration factor was determined by comparing the results of a dynamic pressure survey at the test section, made without the screen installed, with the readings of the manometer connected to the static pressure orifices. As the screen was uniform in construction and extended completely over the throat, it was assumed that the dynamic pressure distribution and the static pressure orifice calibration would be unaffected by the

screen; and, therefore, the calibration factor determined without the screen installed was used for all tests. To check this assumption the dynamic pressure was measured by a manometer connected to a Pitot tube mounted at the test section 14 inches above the model. After a correction for the effect of the model on the Pitot tube had been applied, it was found that the difference between the dynamic pressures as measured by the two methods did not exceed 4 per cent of the value measured by the static plates. The dynamic pressure may, therefore, be as much as 4 per cent in error.

Results

The results of the tests are presented as plots in Figures 2 to 12c, inclusive. Figure 2 shows the results of the sphere tests and is included to indicate the amount of turbulence present for the various test conditions.

The lift data are presented in Figures 3 to 9e inclusive. Figures 3 to 6, inclusive, are plots of the maximum lift coefficient against Reynolds Number for the N.A.C.A. 0006, the Clark Y, the N.A.C.A. 0021, and the U.S.A. 35-A airfoils; and show both scale and turbulence effects on maximum lift. Figures 7a to 9e, inclusive, present complete lift curves, corrected for tunnel wall effects for three of the airfoils, the Clark Y, the N.A.C.A. 0021, and the U.S.N. P.S.6.

The drag data are presented in Figures 10 to 12c, inclusive. Figures 10 and 11 are plots of the minimum profile drag against Reynolds Number for the two symmetrical sections. The results of previous researches on the skin friction of flat plates, taken from References 3 and 5, have also been plotted in Figures 10 and 11. Complete profile drag data for the Clark Y are presented in Figures 12a to c so that the effects of scale and turbulence, not only on minimum profile drag but also on the shapes of the profile drag curves, could be studied.

Discussion

Turbulence, unlike scale, is not readily defined in terms of physical quantities. It may be defined, however, by its effect on the characteristics of certain bodies. The sphere has been used in this investigation. Discussions of this method of defining turbulence are given in References 2 and 3. It will be noted that the critical Reynolds Number for the sphere is in the scale range corresponding to the low scale airfoil tests. Accordingly, the sphere tests may not give a true indication of the turbulence for the high scale tests because of differences in the air flow between high and low scale test conditions. However, it is certain that the structure of the screen was of such a nature as to increase the air stream turbulence at all values of the Reynolds Number.

Scale and turbulence effects on lift.- The value of maximum lift is generally affected by changes in the dynamic scale or Reynolds Number. The N.A.C.A. 0006 airfoil shows a neutral scale effect (Fig. 3) and the N.A.C.A. 0021 airfoil shows a favorable scale effect (Figure 5). The Clark Y, a medium thick cambered airfoil, also shows a favorable scale effect on maximum lift; but the thick cambered airfoils, the U.S.A. 35-A and the U.S.N. P.S.6, show distinctly unfavorable scale effects. Apparently, the nature of the scale effect is not governed by any simple law and seems to bear no definite simple relation to the physical characteristics of the airfoils.

Some of the thick airfoils show further marked scale effects. At low Reynolds Numbers the lift may fall off abruptly after the maximum is reached. As the Reynolds Number is increased, however, these discontinuities disappear and the lift curves resemble in form the more familiar ones common to medium thick and thin airfoils (Figs. 8a and 9e).

The effect of increased turbulence on the shape of the lift curve in the neighborhood of maximum lift is similar to the effect of increased scale (Figs. 8a and 9e). There are included in Figures 9a to e the results of previous tests, because they permit a comparison for three degrees of turbulence. These tests were conducted in the Variable Density Wind Tunnel operated as an open-throat type (Reference 4). It will be noted that the curves for low scale data from the open-throat tunnel show a sudden drop

in lift to a value approximately half the maximum. The data from the closed-throat tunnel, which has a more turbulent air stream than the open throat, show the sudden drop in lift, but the difference between the high and low values is smaller than that shown by the open-throat tunnel. The discontinuity disappears altogether when the turbulence of the air stream is increased by the addition of the screen.

The effects of turbulence on the value of maximum lift are as complicated as the effects of scale. Over the scale range covered the added turbulence decreases the maximum lift of the N.A.C.A. 0006 and U.S.A. 35-A airfoils. The effect of turbulence on the maximum lift of the Clark Y and N.A.C.A. 0021 airfoils, however, is dependent upon the scale or Reynolds Number of the tests. At very low values of the Reynolds Number turbulence has an unfavorable effect on the maximum lift of these two airfoils, but at high values of the Reynolds Number the turbulence effect is markedly favorable.

Variations in turbulence also change the scale effect on maximum lift. As pointed out, the effect on the maximum lift of certain airfoils is dependent on the Reynolds Number. The results for the N.A.C.A. 0021 airfoil show an increased slope of the curve of maximum lift coefficient plotted against Reynolds Number (Fig. 5) with increased turbulence, whereas the results for the Clark Y airfoil, like the results for the N.A.C.A. 0021, show a slope difference but resemble closely the

turbulence effects on the sphere. The curve of maximum lift coefficient against Reynolds Number (Fig. 4) apparently moves to the left as the turbulence is increased. In other words, the rapid change in maximum lift coefficient occurs at lower values of the Reynolds Number. The effect of increased scale on the maximum lift of airfoils that show unfavorable scale effects (the U.S.N. P.S.6 and the U.S.A. 35-A) or neutral scale effects (the N.A.C.A. 0006) when the turbulence is small becomes unimportant when the turbulence is increased.

Scale and turbulence effects on profile drag.- The effects of scale and turbulence on the drag of bodies are particularly complicated because of the various types of forces which together make up the total drag. It is of interest to compare the drag of the symmetrical airfoils with that of a flat plate. The air force on a flat plate, when it is placed parallel to the relative air flow, is wholly skin friction. The effects of both scale and turbulence on the drag of flat plates have been investigated.

Curves, representing the results of these investigations (Reference 5), are presented, together with the results of the present investigation on airfoils, in Figures 10 and 11. It will be noted from the figures that the drag of the flat plate is dependent not only on the dynamic scale or Reynolds Number, but also on the condition of flow in the boundary layer. If the flow in the boundary layer is wholly laminar, the measured

drags will fall along the lower line and if wholly turbulent the measured drags will fall along the upper line. If the flow in the boundary layer is, however, partly laminar and partly turbulent, the measured drags will fall somewhere between the upper and lower lines and along a curve similar to the transition curve shown. It must also be remembered that the Reynolds Number at which the transition from laminar to turbulent flow begins is dependent on the initial turbulence of the air stream.

The drag data for the N.A.C.A. 0006 airfoil (Fig. 10) agree closely with the corresponding flat plate data. The scale effect curve, which was obtained without the screen in place, resembles the transition curve for the flat plate. The similarity is not very surprising, as this particular airfoil physically approximates the flat plate. Because it is symmetrical and very thin, the pressure drag and the pressure gradients, the quantities which cause the flow to differ from that about a flat plate, are not of major importance. Increased turbulence, as would be predicted from the behavior of the flat plate, causes an increase in the drag coefficient; and the data taken with the screen installed are very similar to the drag data for the flat plate when the boundary layer flow is turbulent.

The scale effect curves for the N.A.C.A. 0021 airfoil are similar in form to the corresponding curves for the N.A.C.A.

0006 airfoil. The actual drag values are, however, much higher, a difference which is not surprising in view of the fact that the pressure drag constitutes a large part of the total drag of thick airfoils, such as the N.A.C.A. 0021. The effect of turbulence at any particular value of the Reynolds Number is noteworthy. Over the scale range covered, increased turbulence results generally in increased drag values. It may be noted, however, that the difference between the results of the tests made with and without the screen installed tends to become smaller as the Reynolds Number is increased.

Scale and turbulence effects on profile drag are evident, not only from the minimum value but also from the shape of the profile drag curves. At low scale the data taken without the screen for the Clark Y airfoil (Figs. 12a to c) show a rapid rise in the drag coefficient with decreasing lift coefficients at low values of the lift coefficient. As the Reynolds Number is increased the increase in the drag coefficient takes place at higher values of the lift coefficient, but becomes smaller and eventually disappears. The scale or Reynolds Number has but little effect on the shape of the profile drag curve for high values of the lift coefficient. Turbulence, on the other hand, does have a marked effect on the shape of the profile drag curve at high values of the lift coefficient. At low Reynolds Numbers the rise in the drag coefficient occurs at lower values of the lift coefficient and is, in general, steeper except near

the burble point. As the Reynolds Number is increased, however, the results of the tests with the screen resemble closely the results of the tests without the screen. In general, the drag results indicate that the added turbulence tends to become of small importance at very high Reynolds Numbers.

Conclusions

General conclusions can not be formed with certainty from the results of this investigation, because of its limited scope. However, these results support the following generalizations:

1. Increased scale has a favorable effect on the maximum lift of thick symmetrical airfoils and medium thick cambered airfoils, an unfavorable effect on the maximum lift of thick cambered airfoils, and a neutral effect on the maximum lift of thin symmetrical airfoils.

2. Increased turbulence at high values of the Reynolds Number increases the maximum lift of airfoils that show favorable scale effects on maximum lift.

3. Increasing either the value of the Reynolds Number or the turbulence of the air stream eliminates lift curve discontinuities.

4. Within the range of the Reynolds Number common to present-day aircraft, the minimum profile drag decreases with increasing Reynolds Number.

5. The effects of turbulence on the profile drag of airfoils tend to become of small importance at very high values of the Reynolds Number.

6. The effects of large increases in the Reynolds Number on the aerodynamic characteristics of airfoils are more important than the effects of large increases in turbulence.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 23, 1931.

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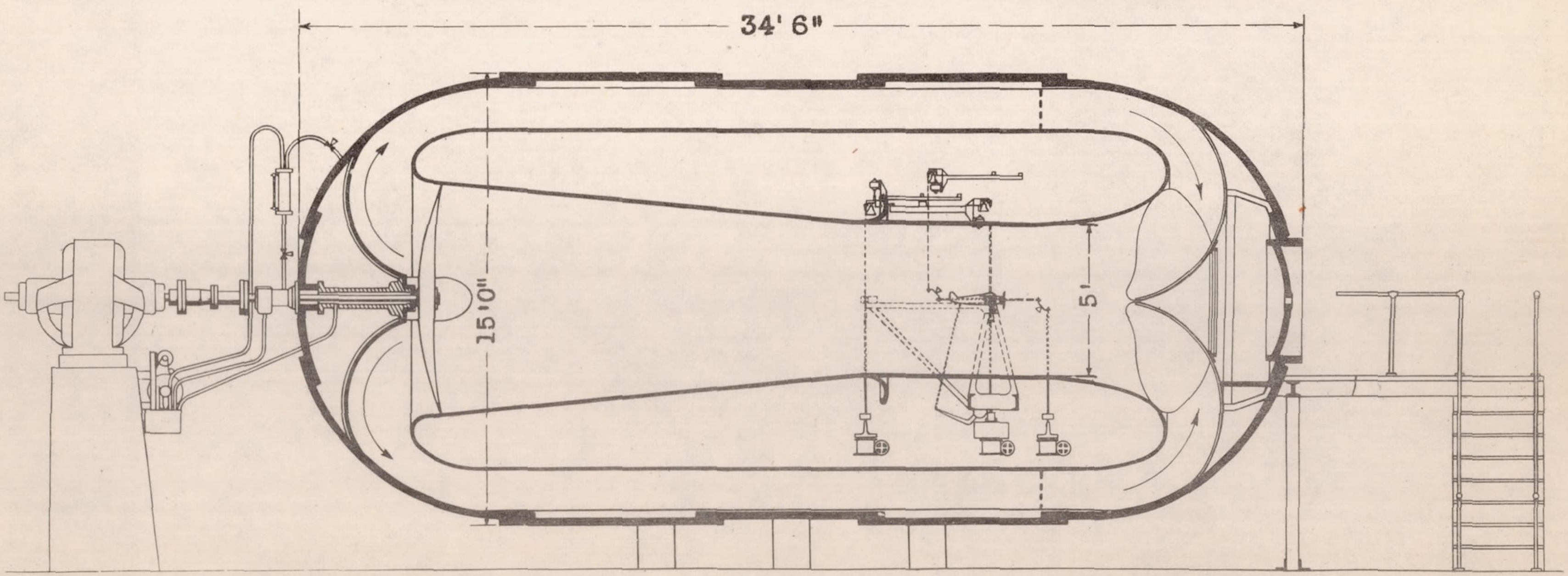


Fig. 1 The modified closed throat variable density wind tunnel.

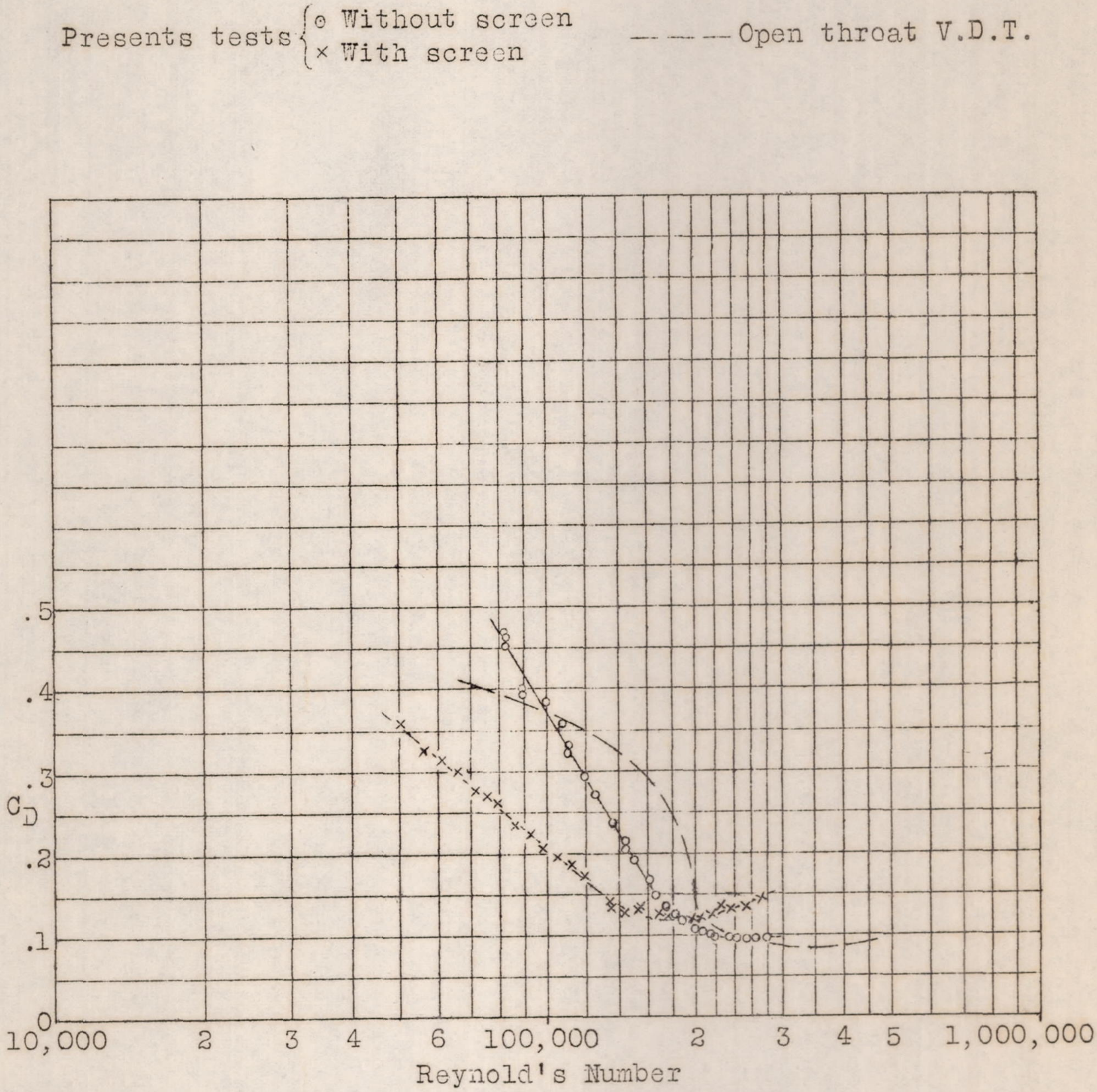


Fig. 2 Drag of 20 cm sphere

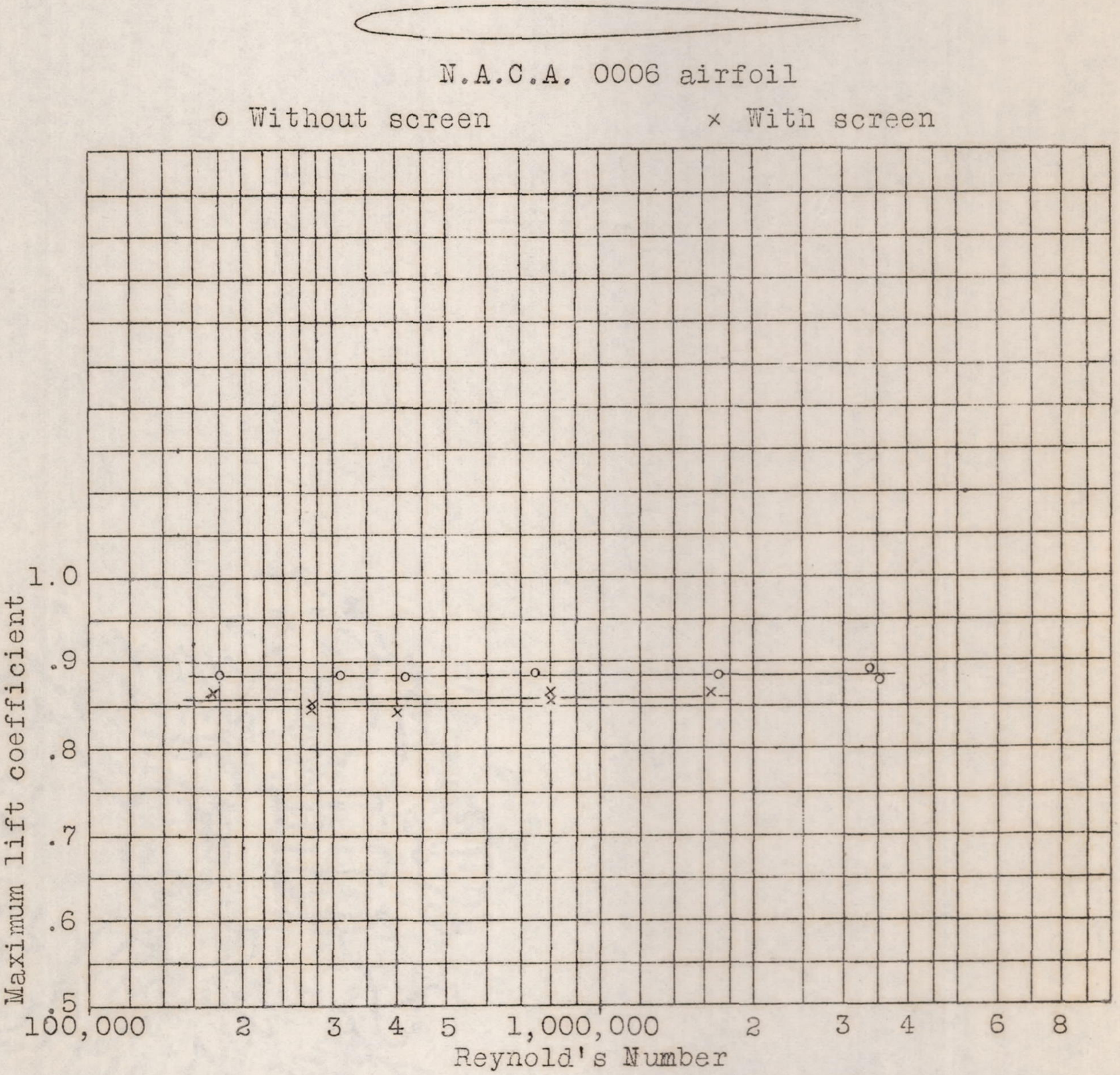


Fig. 3 Scale and turbulence effects on maximum lift.

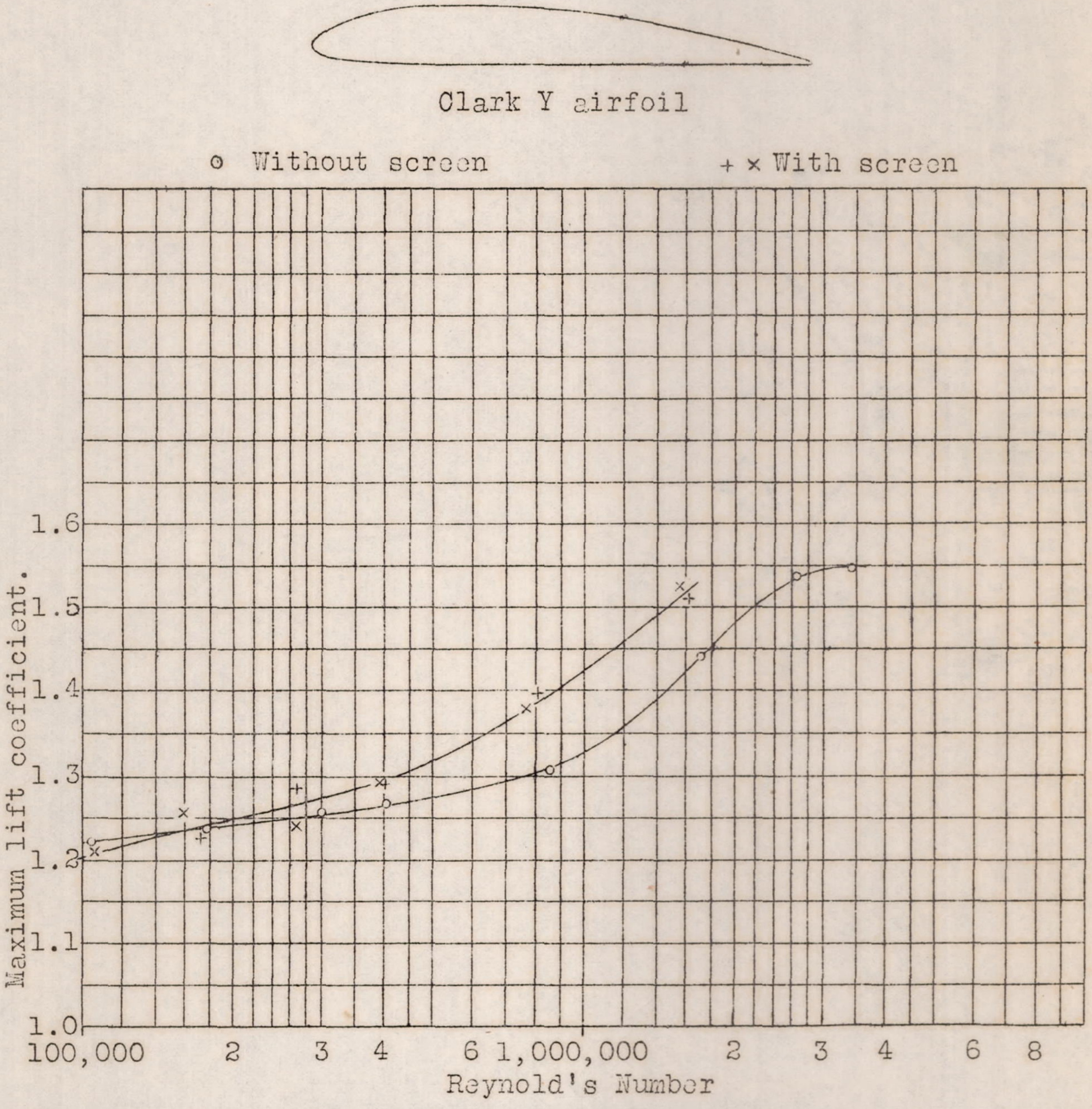


Fig. 4 Scale and turbulence effects on maximum lift.

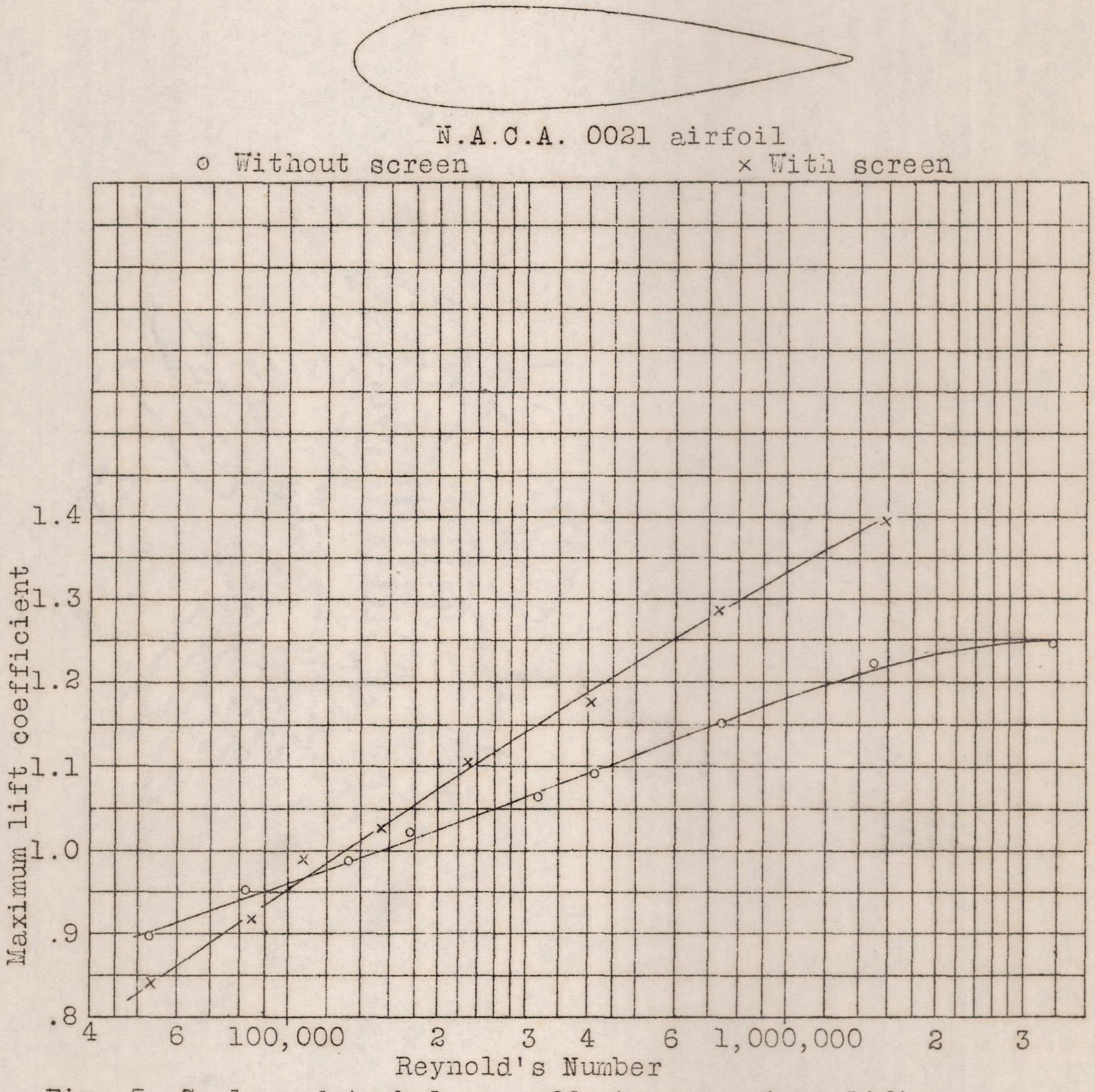


Fig. 5 Scale and turbulence effects on maximum lift.

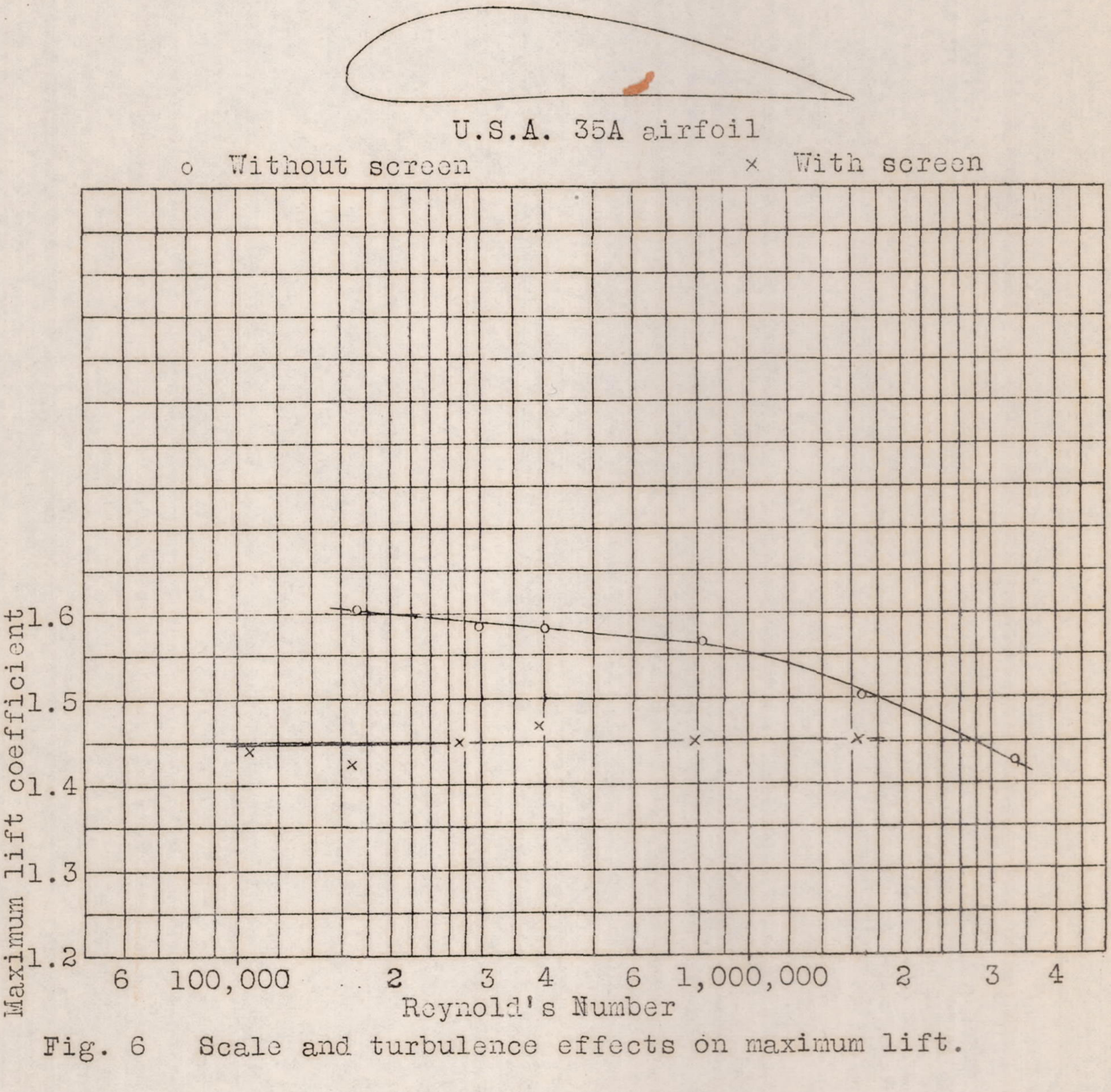
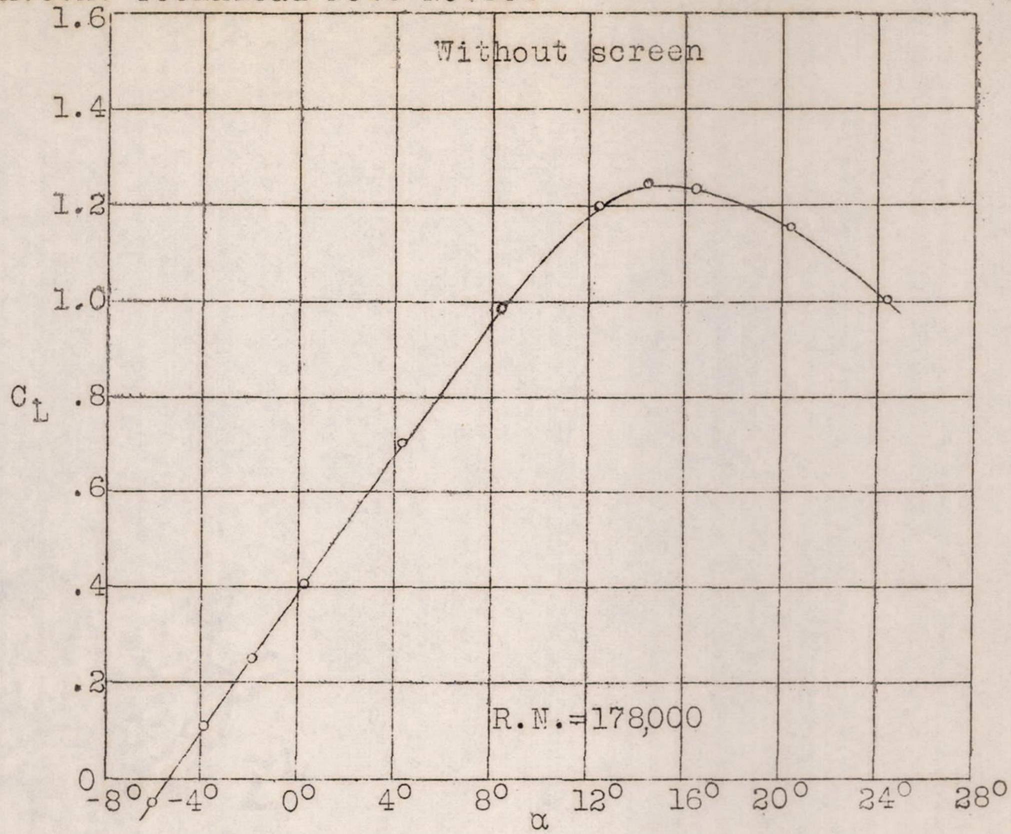


Fig. 6 Scale and turbulence effects on maximum lift.



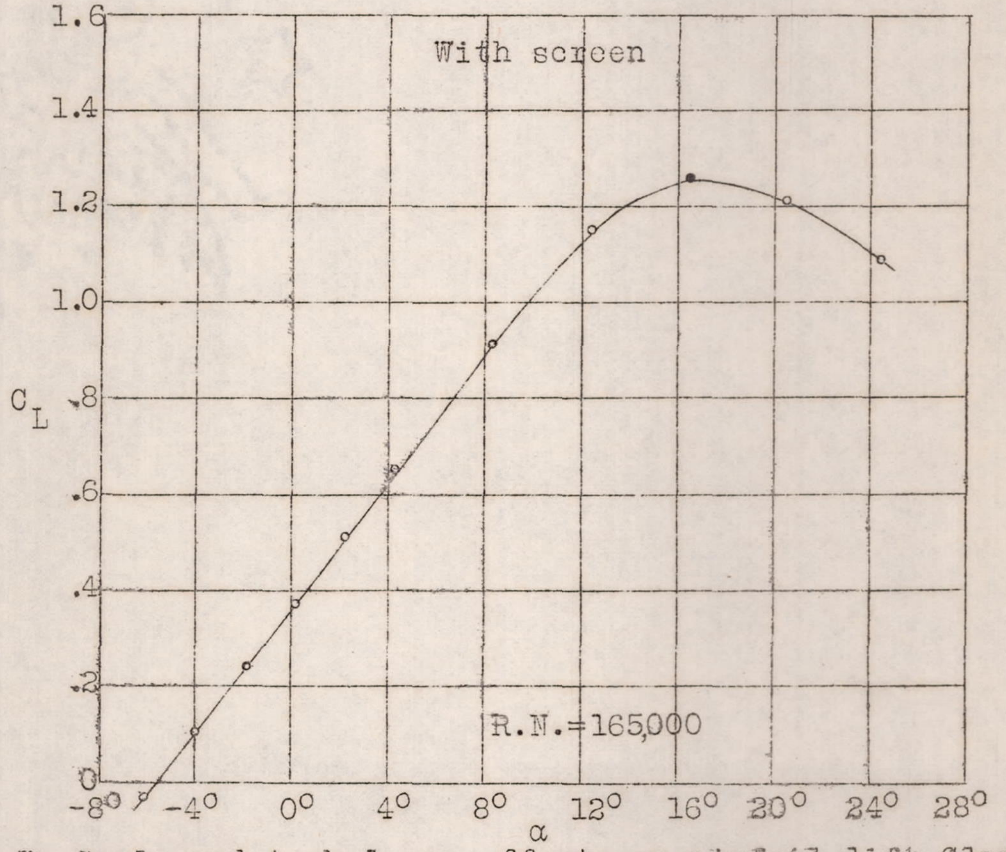
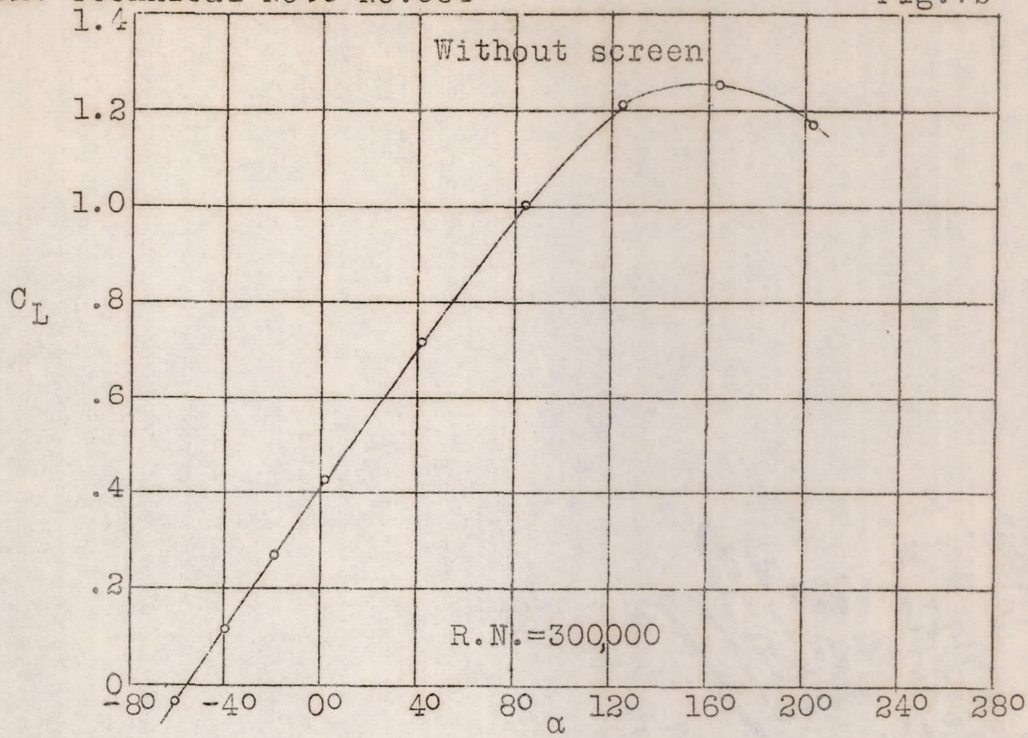


Fig.7a Scale and turbulence effects on airfoil lift, Clark-Y airfoil



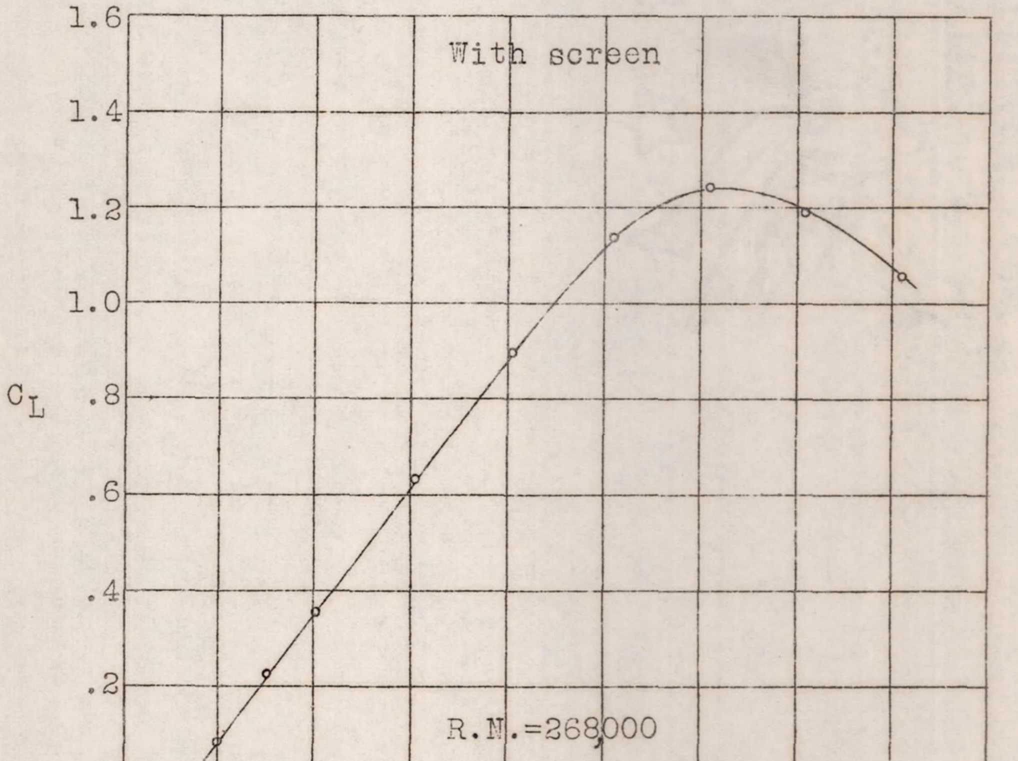
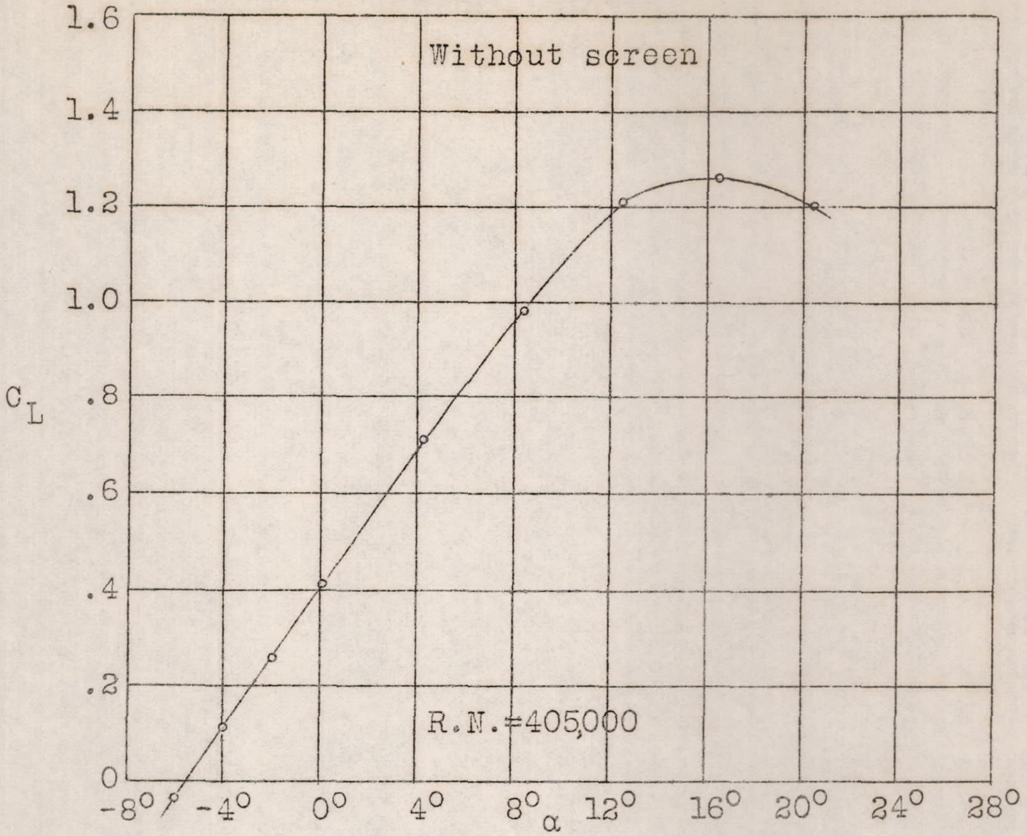


Fig.7b Scale and turbulence effects on airfoil lift, Clark-Y airfoil.



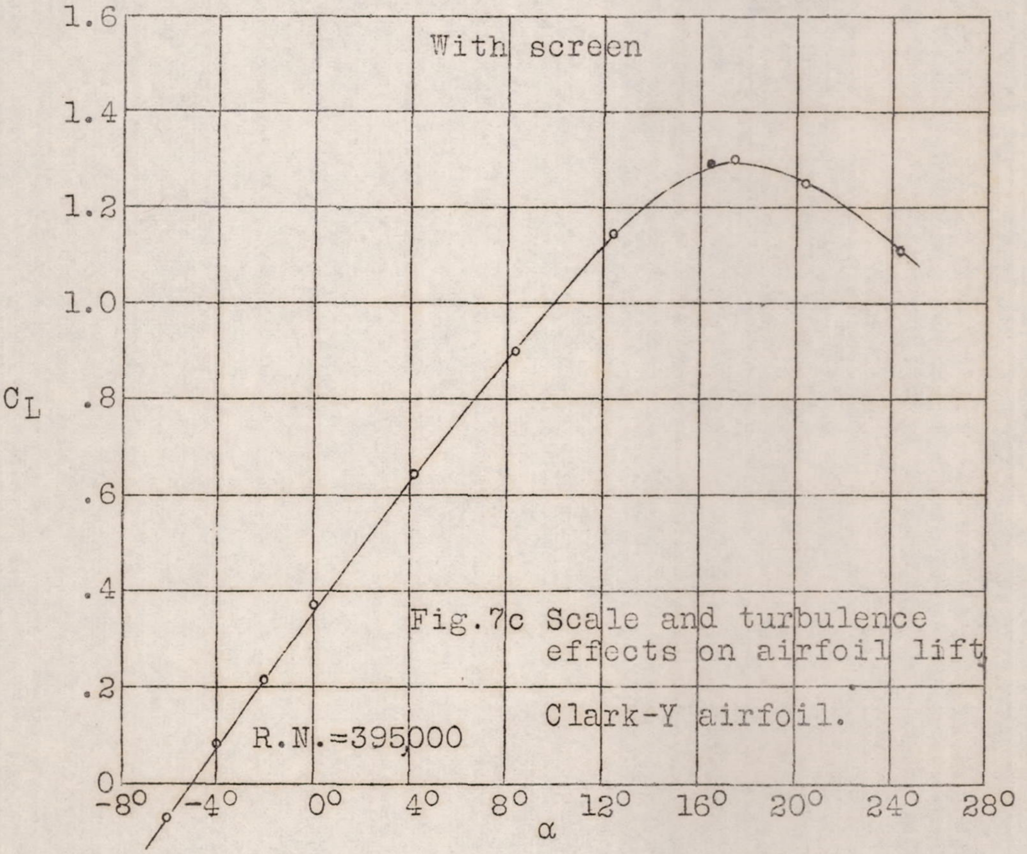
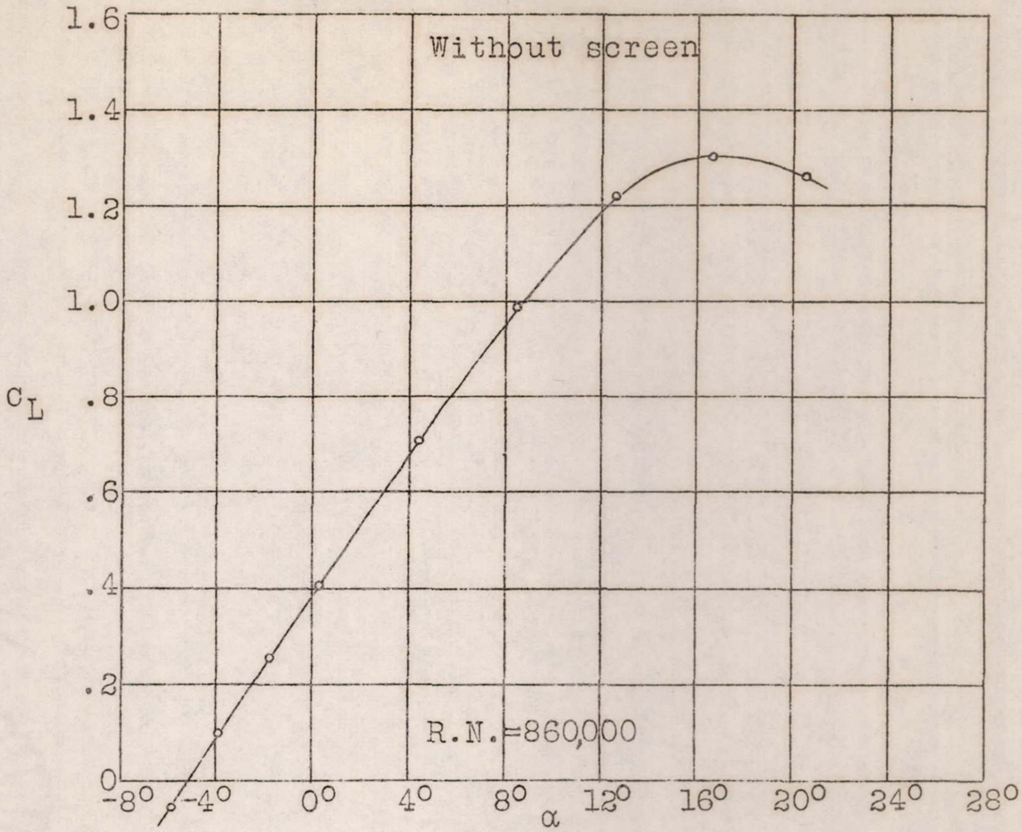


Fig.7c Scale and turbulence effects on airfoil lift, Clark-Y airfoil.



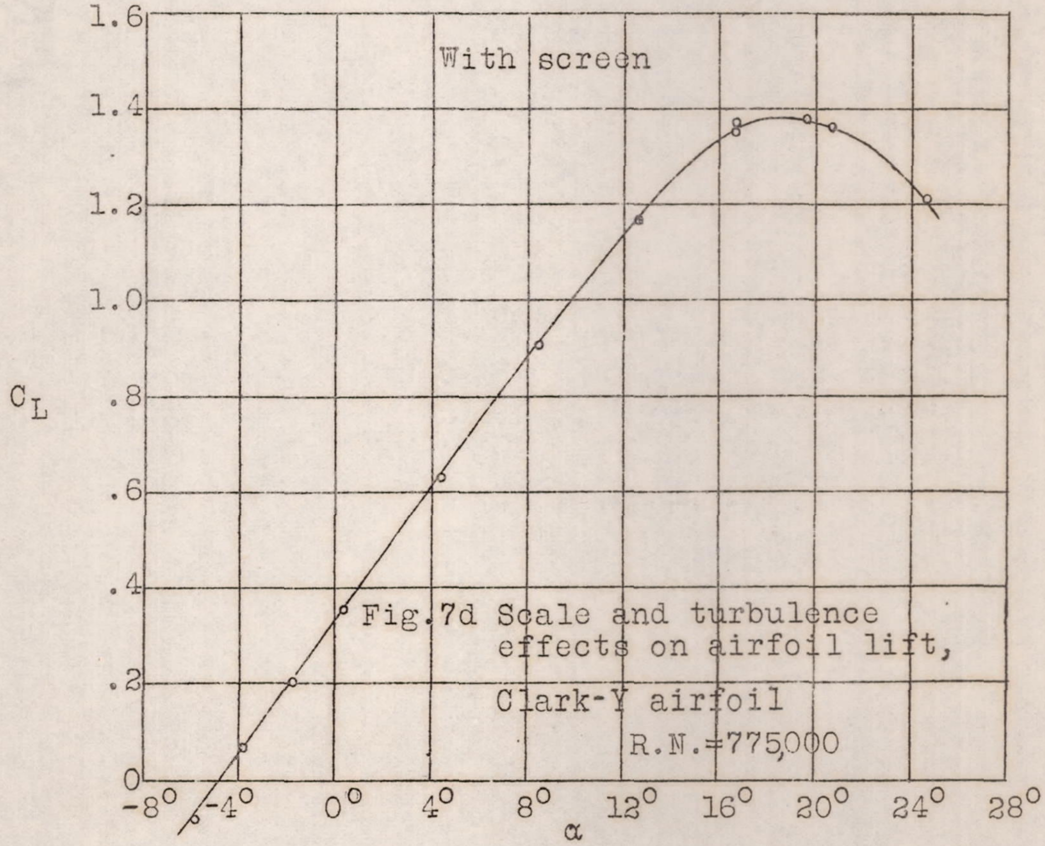
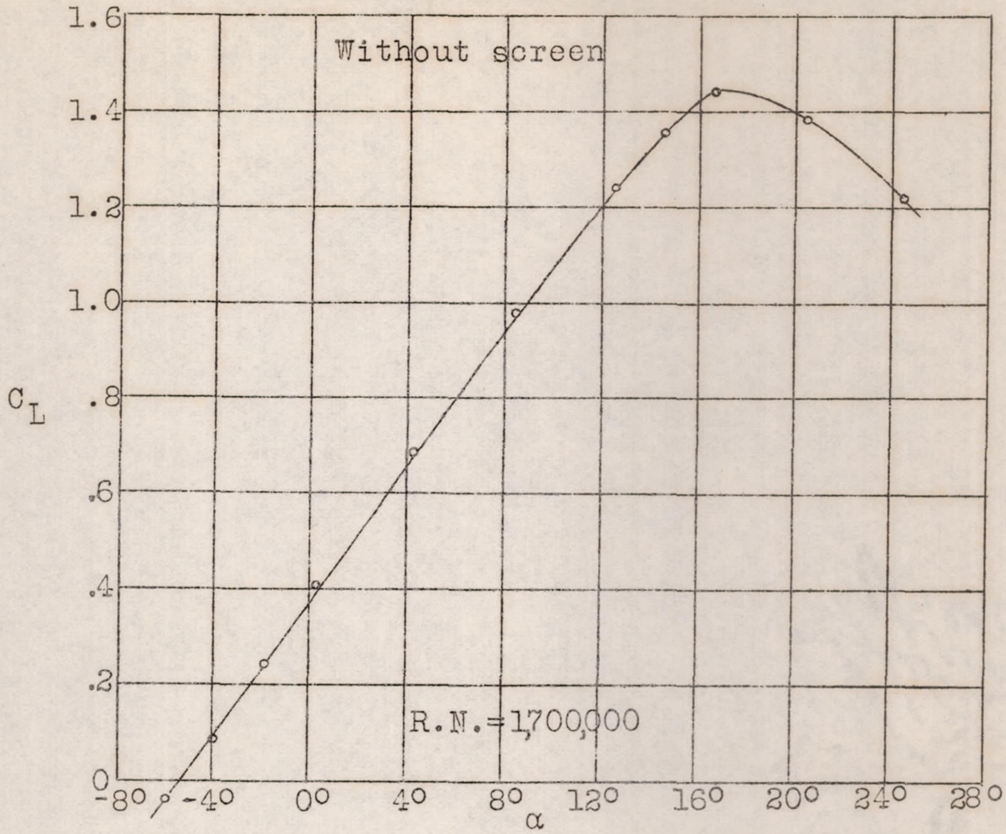


Fig.7d Scale and turbulence effects on airfoil lift, Clark-Y airfoil



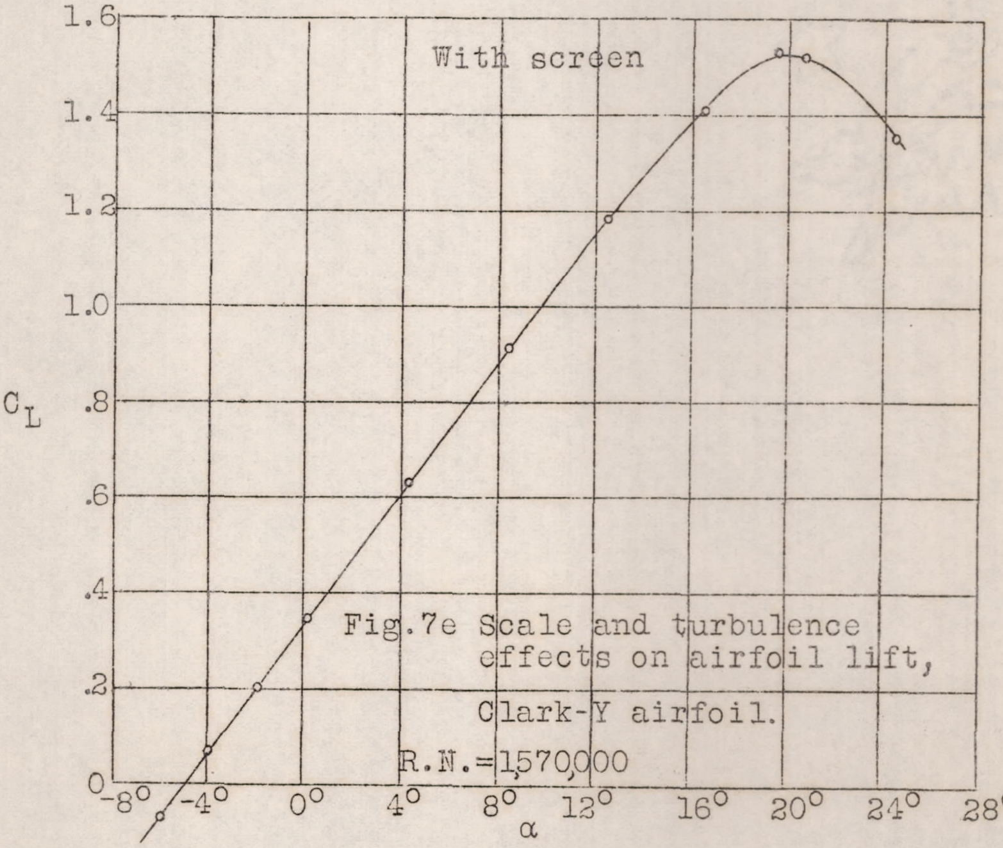
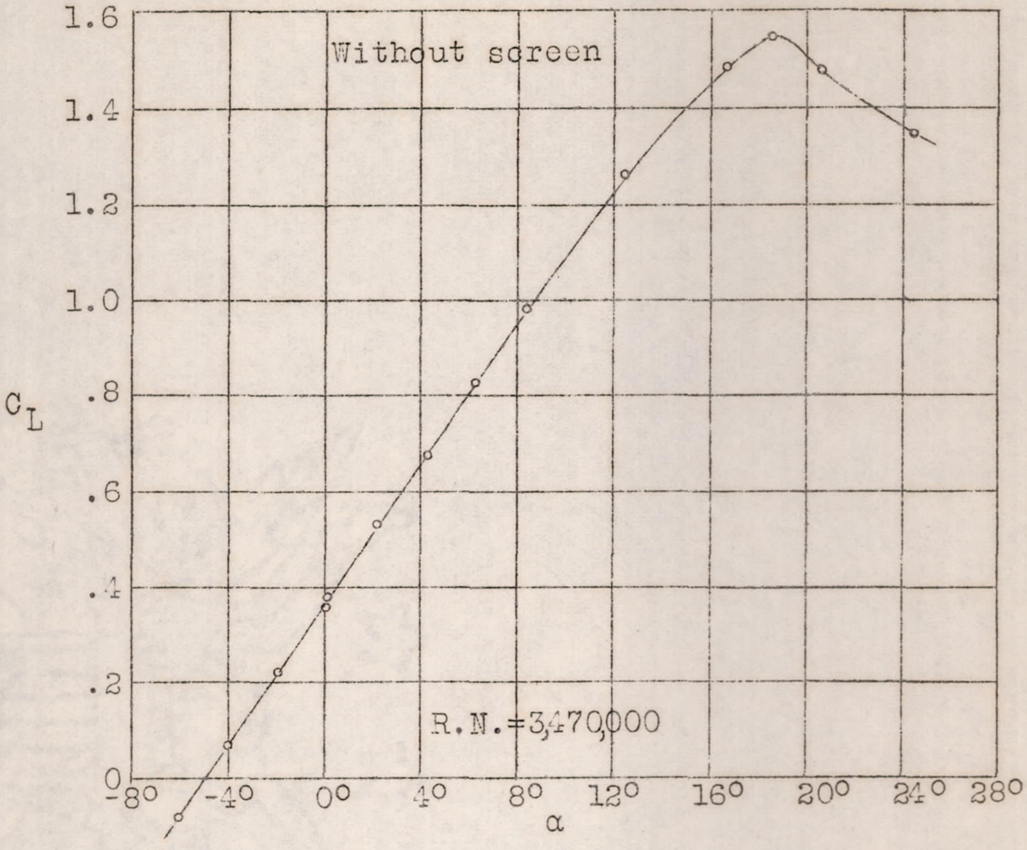
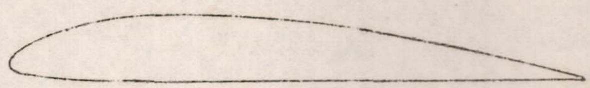


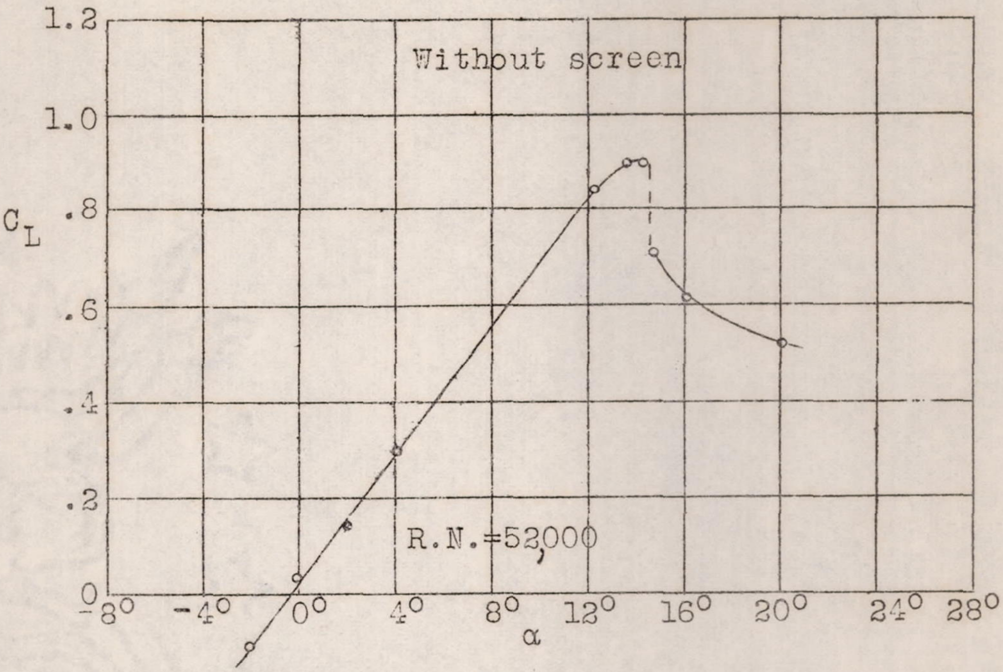
Fig.7e Scale and turbulence effects on airfoil lift, Clark-Y airfoil.





Clark Y airfoil

Fig.7f Scale and turbulence effects on airfoil lift, Clark-Y airfoil.



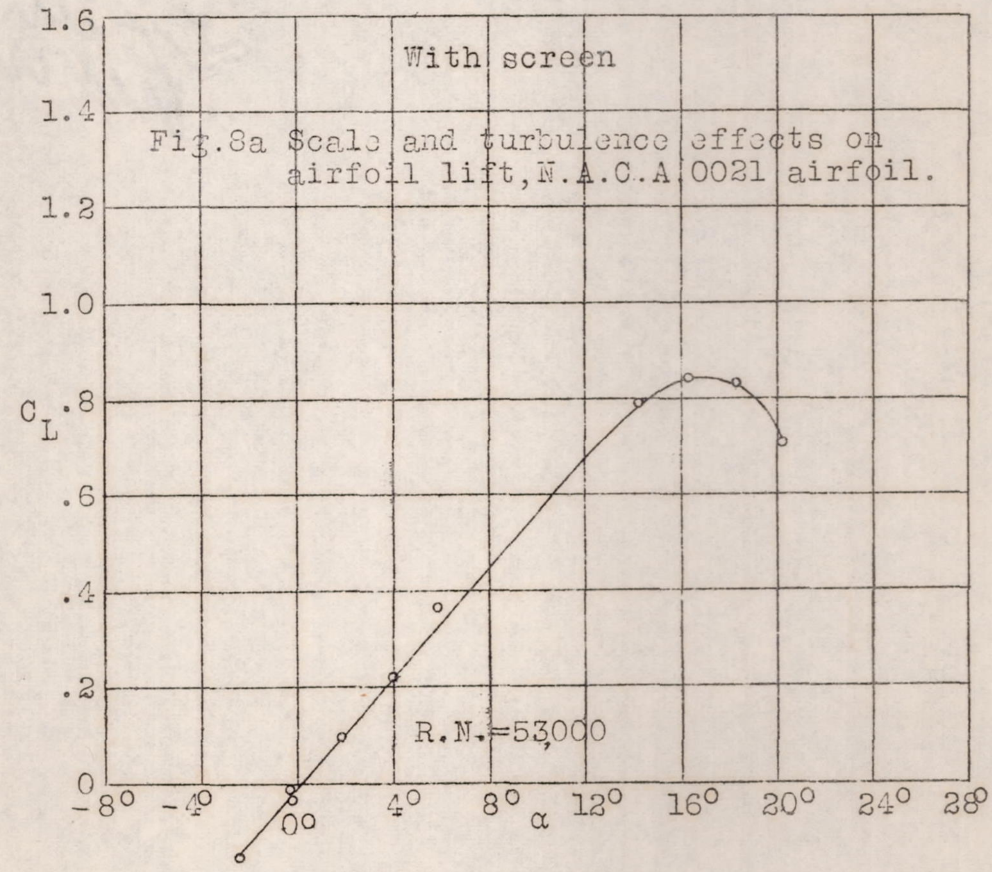
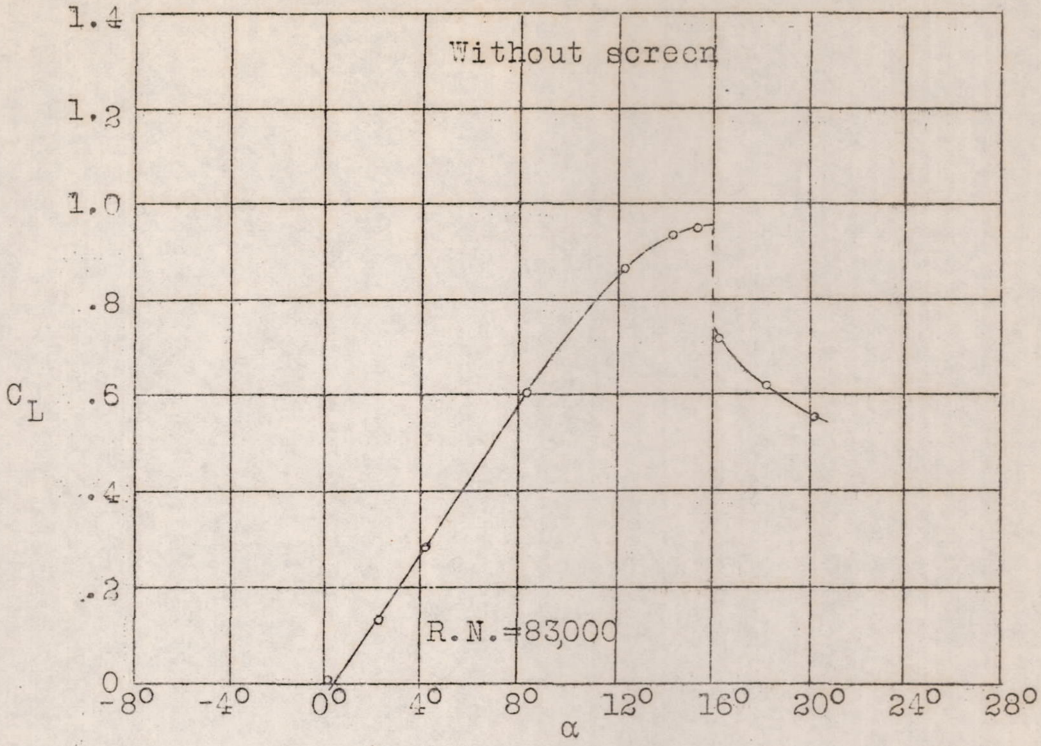


Fig.8a Scale and turbulence effects on airfoil lift, N.A.C.A. 0021 airfoil.



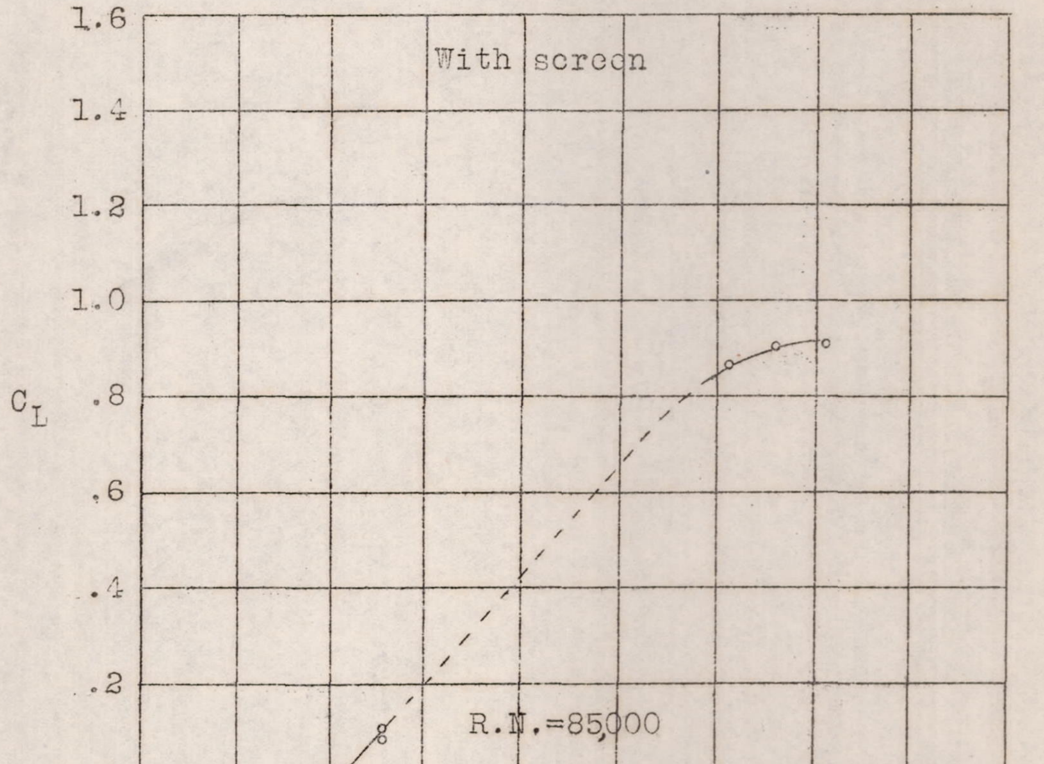
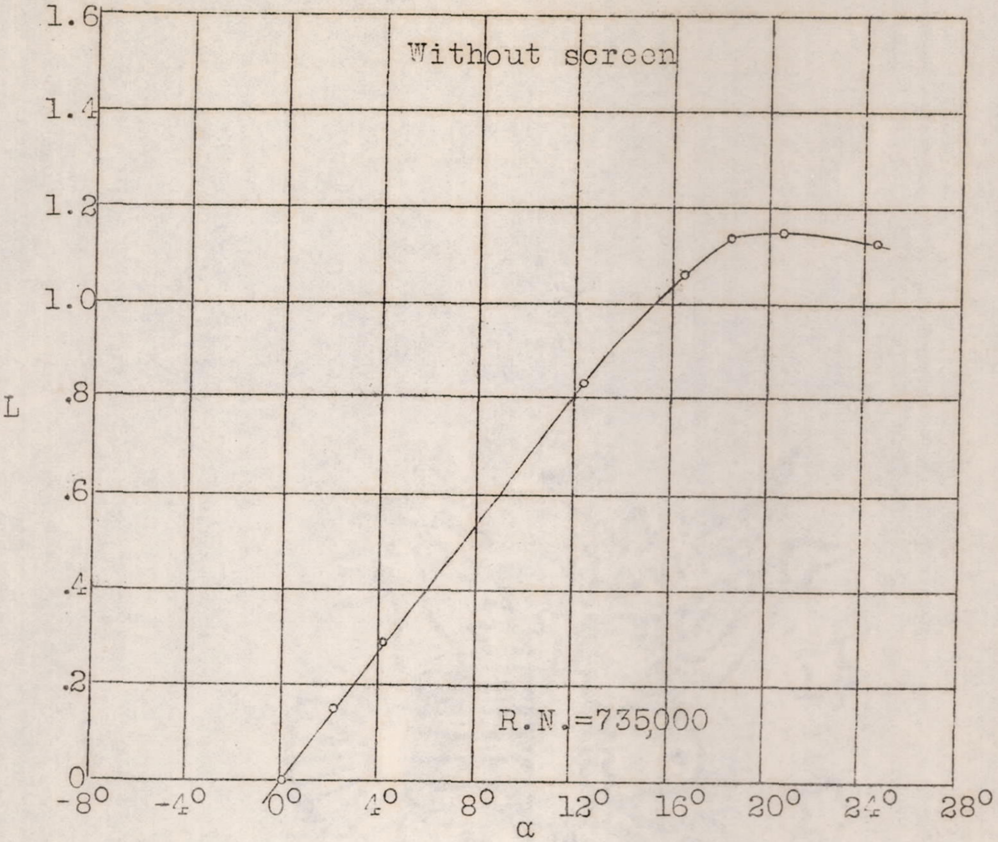


Fig.8b Scale and turbulence effects on airfoil lift, N.A.C.A. 0021 airfoil.



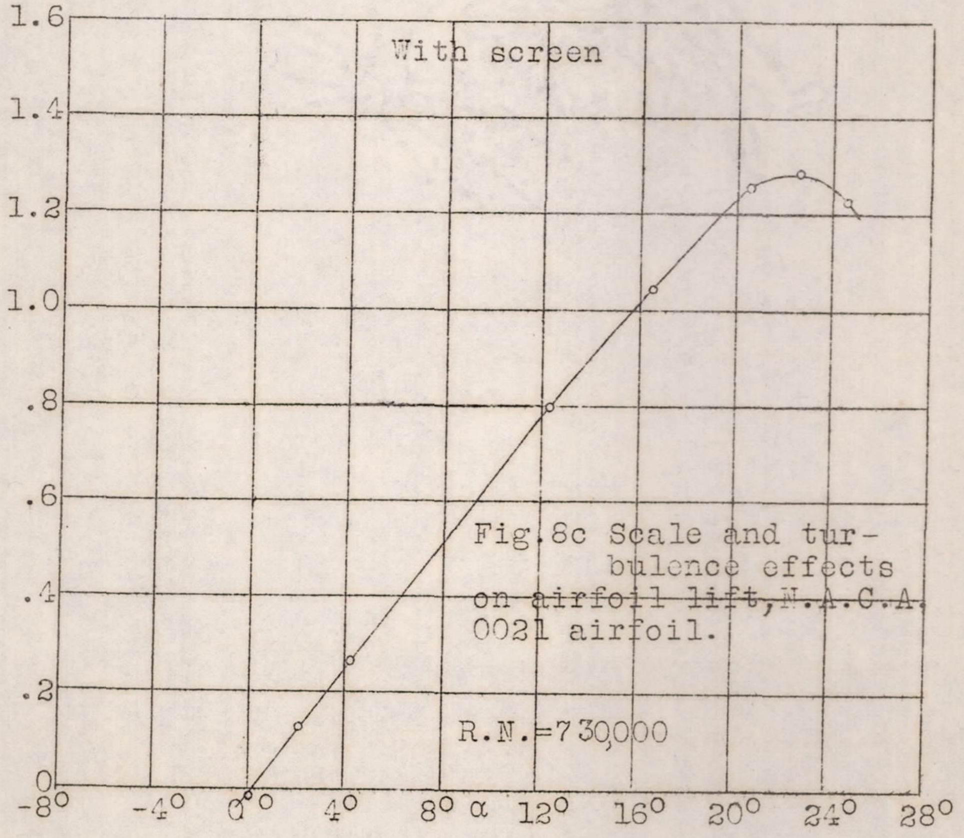


Fig.8c Scale and turbulence effects on airfoil lift, N.A.C.A. 0021 airfoil.

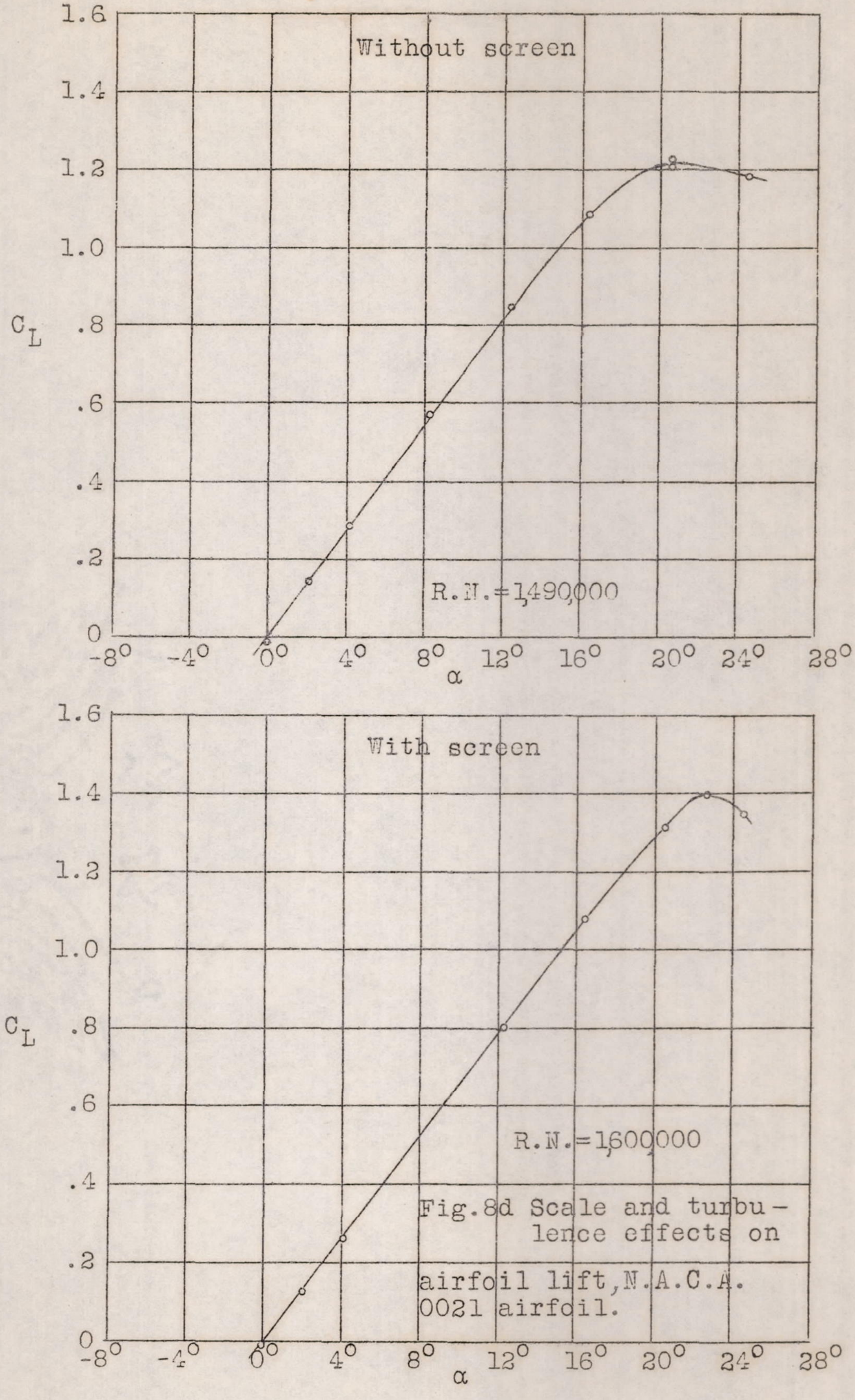
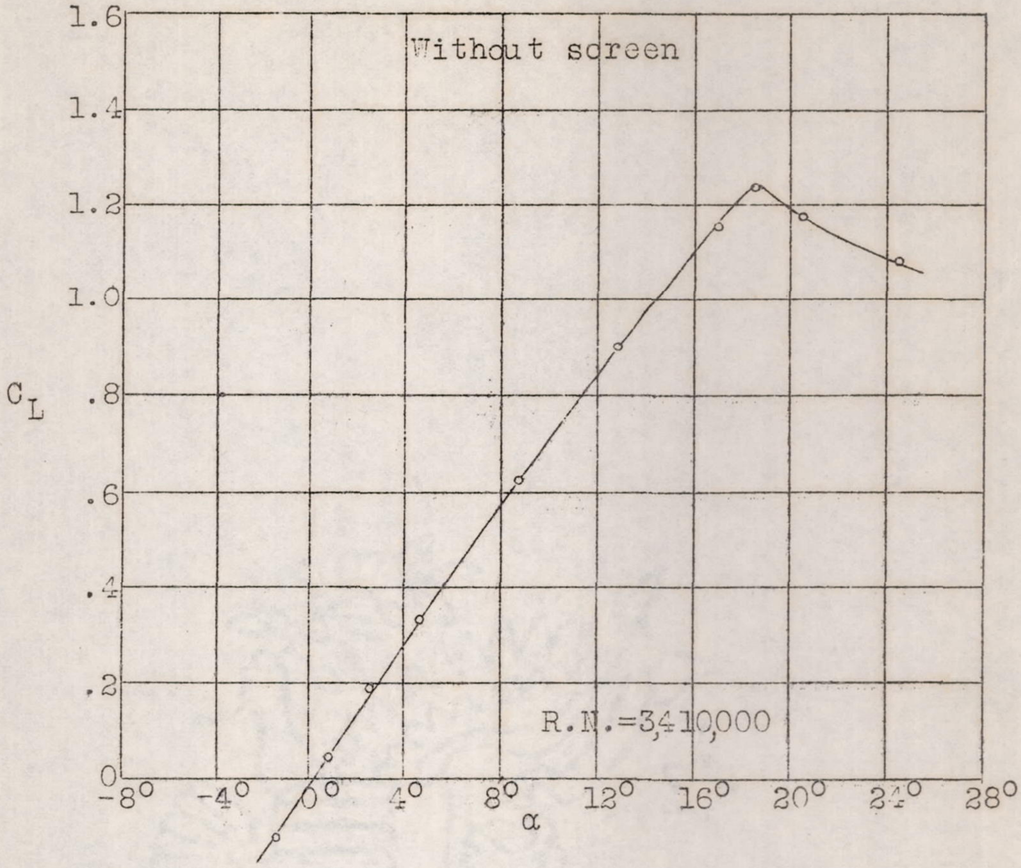
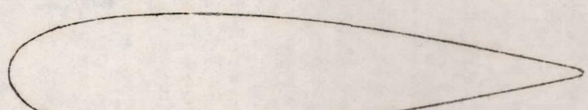


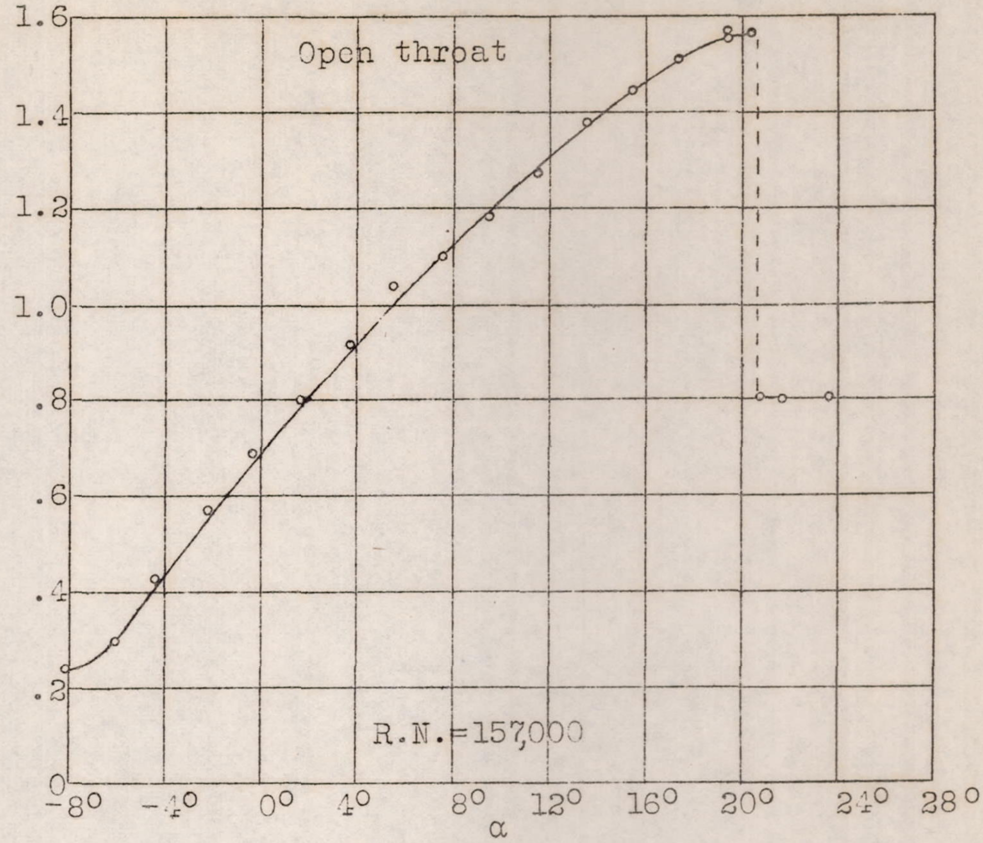
Fig.8d Scale and turbulence effects on airfoil lift, N.A.C.A. 0021 airfoil.





N.A.C.A.0021 airfoil

Fig.8e Scale and turbulence effects on airfoil lift, N.A.C.A. 0021 airfoil.



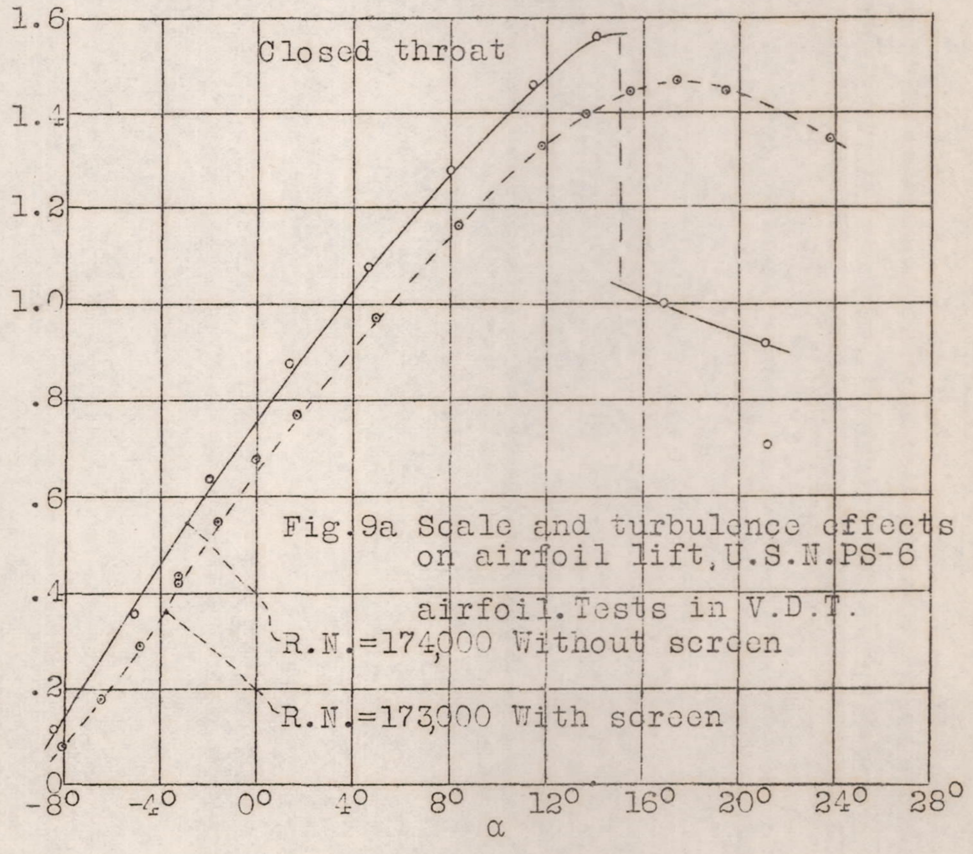
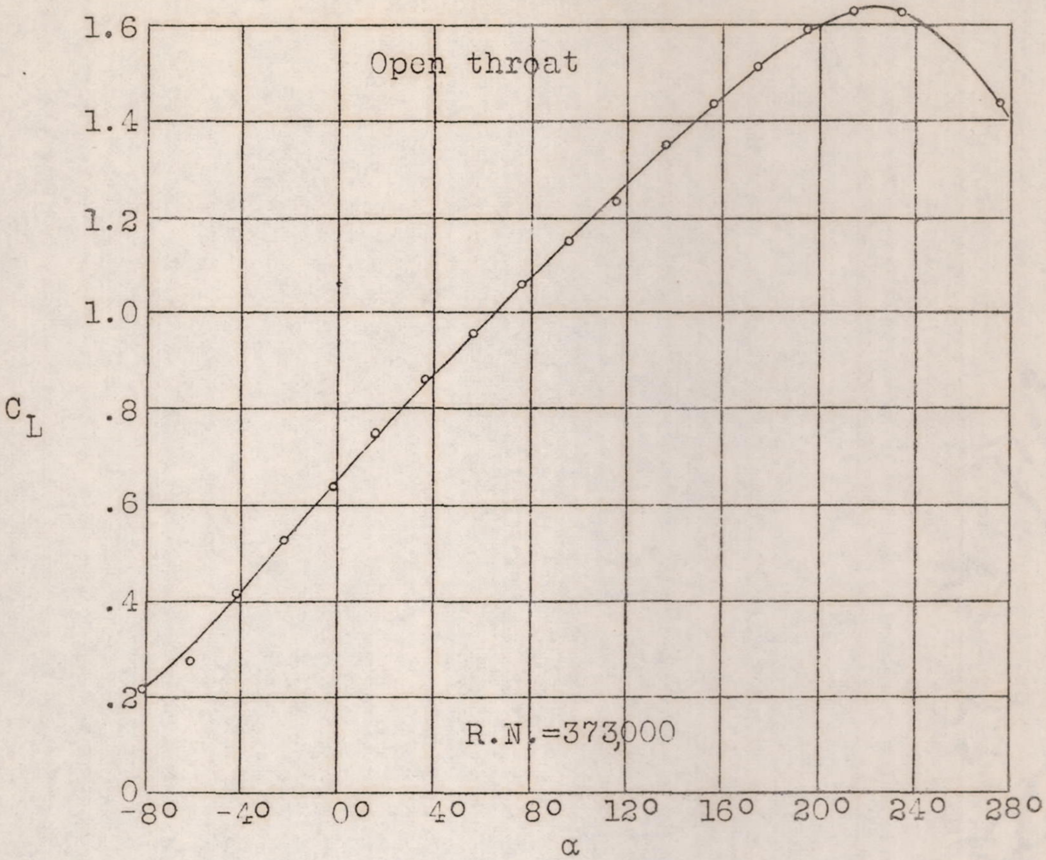
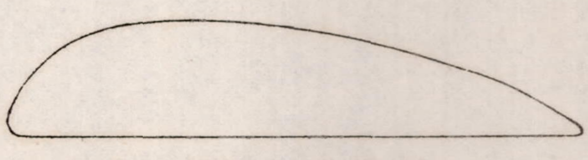


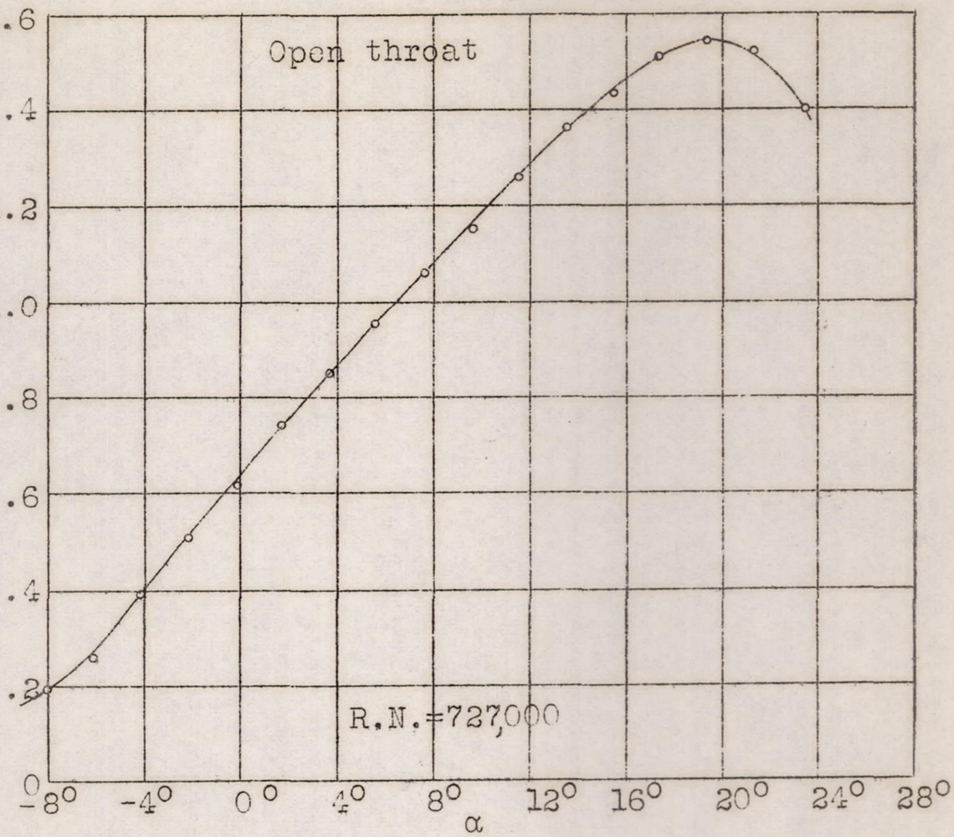
Fig.9a Scale and turbulence effects on airfoil lift, U.S.N. PS-6 airfoil. Tests in V.D.T.

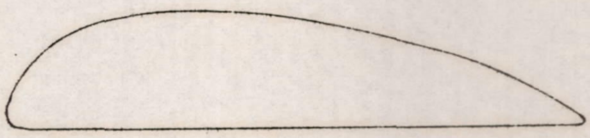




U.S.N. PS-6 airfoil

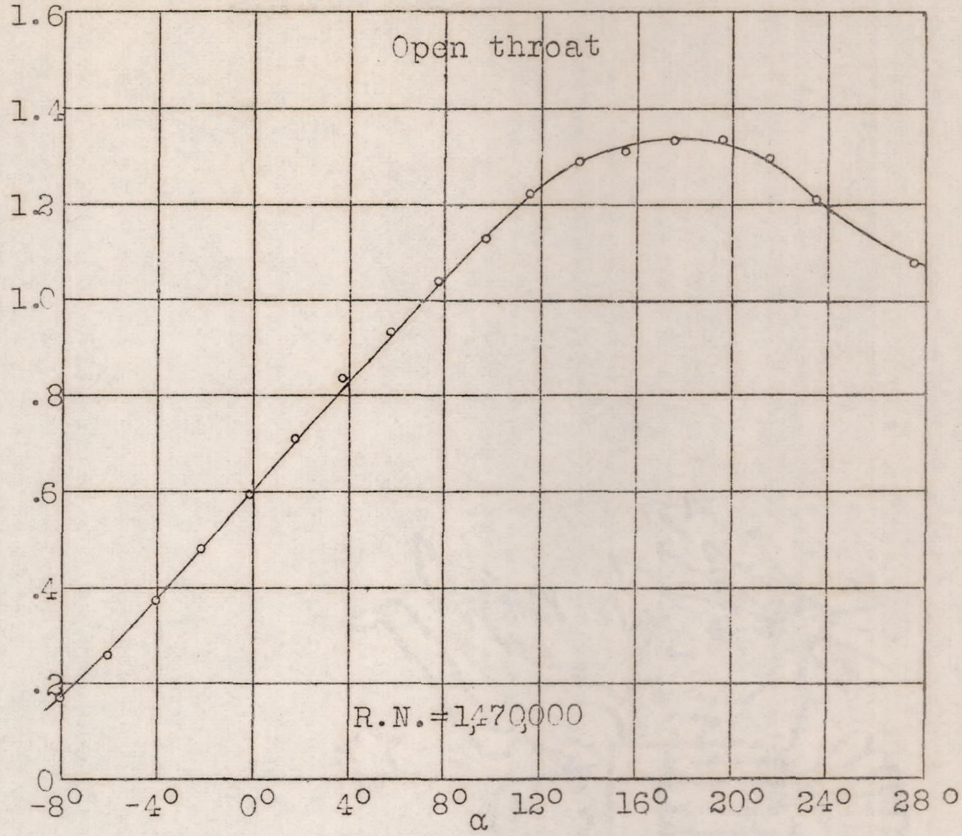
Fig.9b Scale and turbulence effects on airfoil lift, U.S.N. PS-6 airfoil.Tests in V.D.T.





U.S.N.PS-6 airfoil

Fig.9c Scale and turbulence effects on airfoil lift.U.S.N. PS-6 airfoil.Tests in V.D.T.



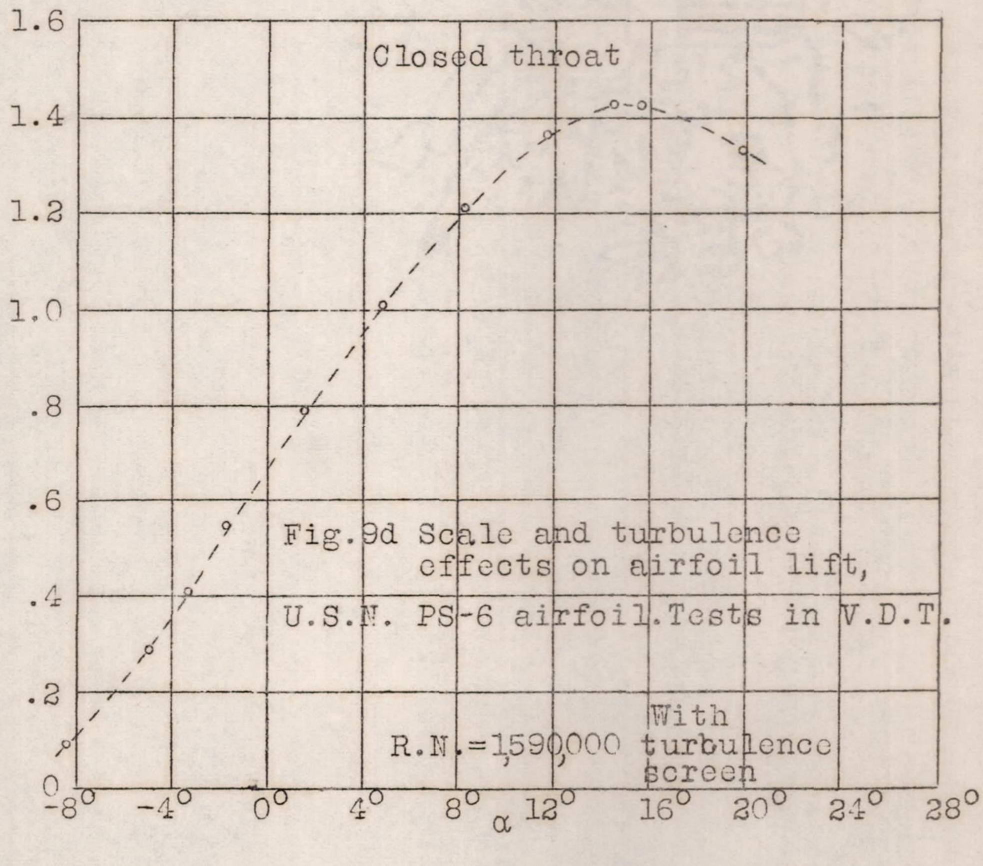
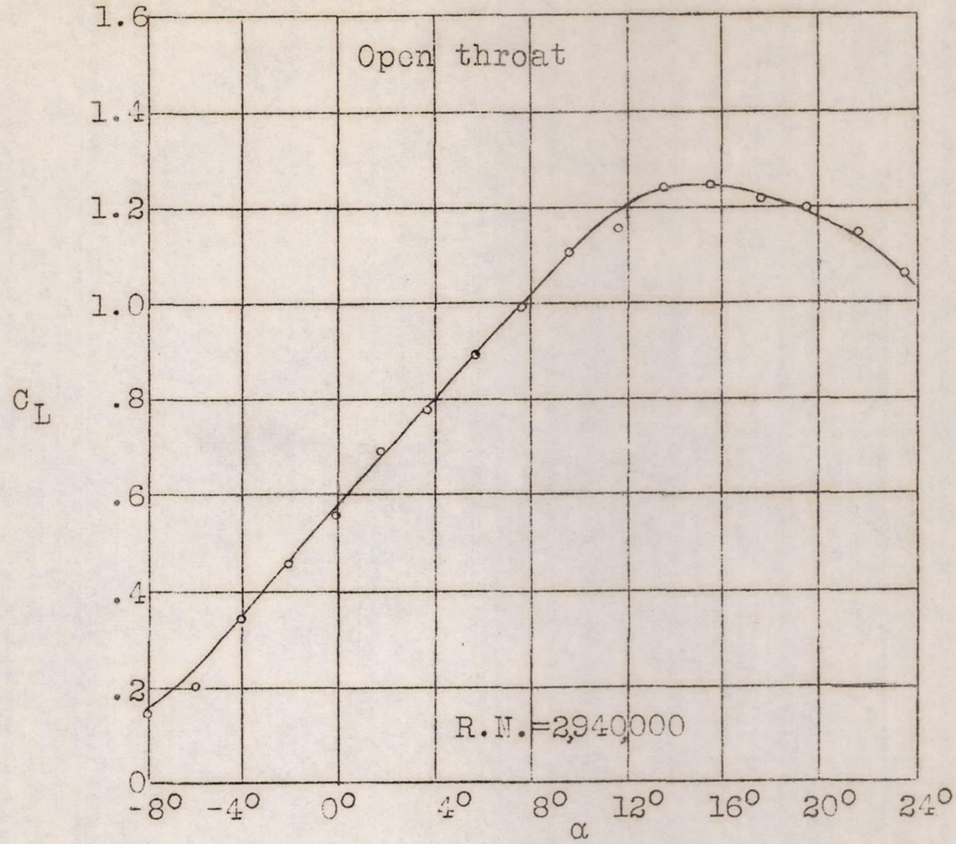


Fig.9d Scale and turbulence effects on airfoil lift,

U.S.N. PS-6 airfoil. Tests in V.D.T.



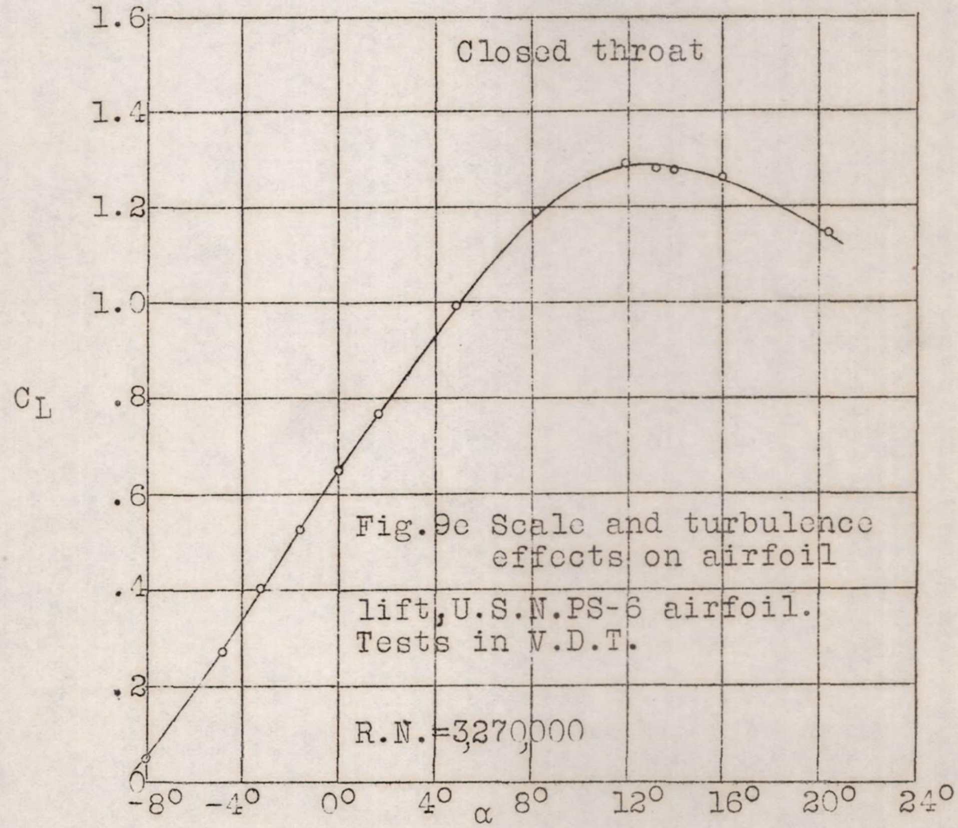


Fig.9c Scale and turbulence effects on airfoil lift, U.S.N.PS-6 airfoil. Tests in V.D.T.

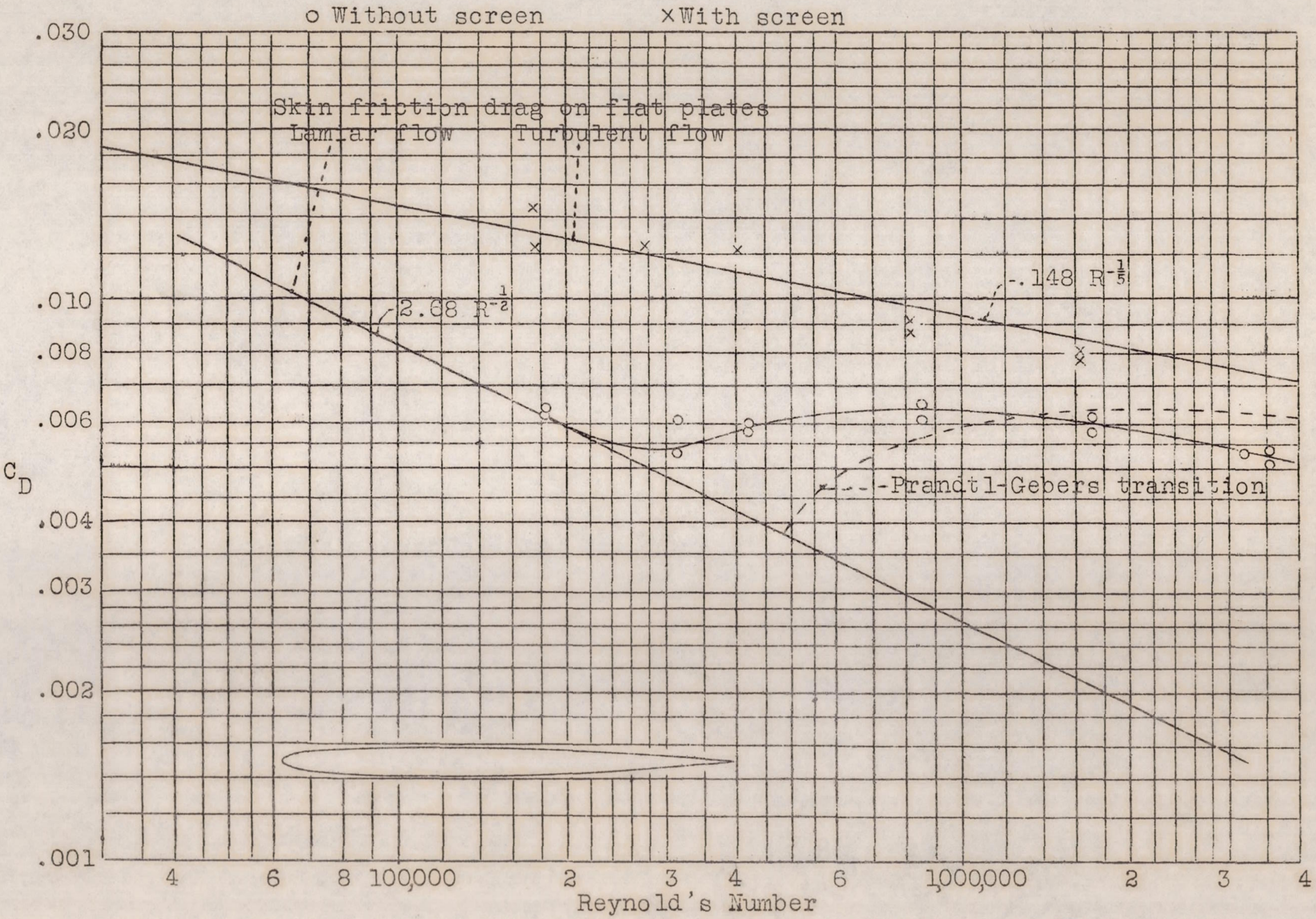


Fig.10 Scale and turbulence effects on minimum drag, N.A.C.A. 0006 airfoil.

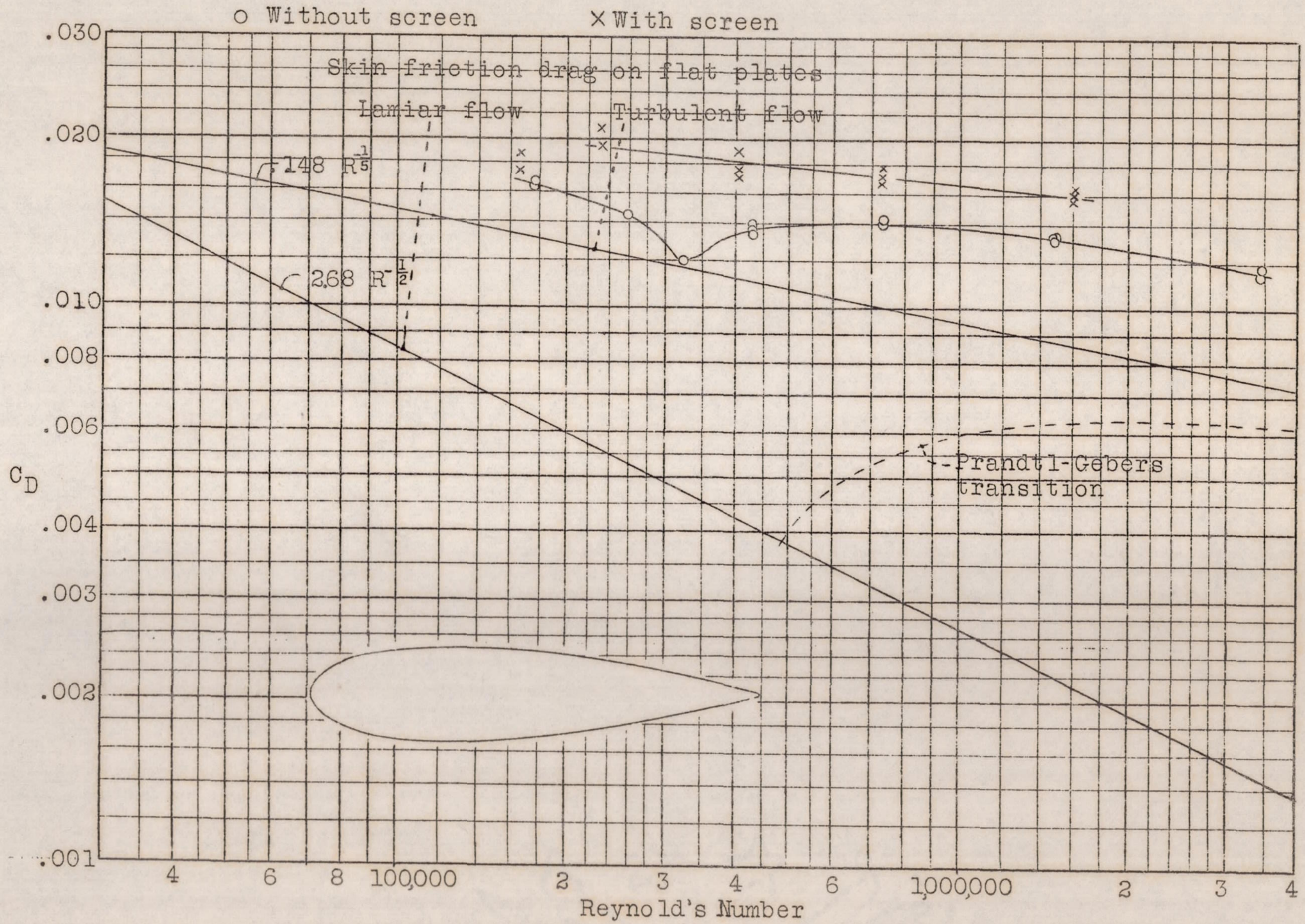


Fig.11 Scale and turburlence effects on minimum drag, N.A.C.A. 0021 airfoil.

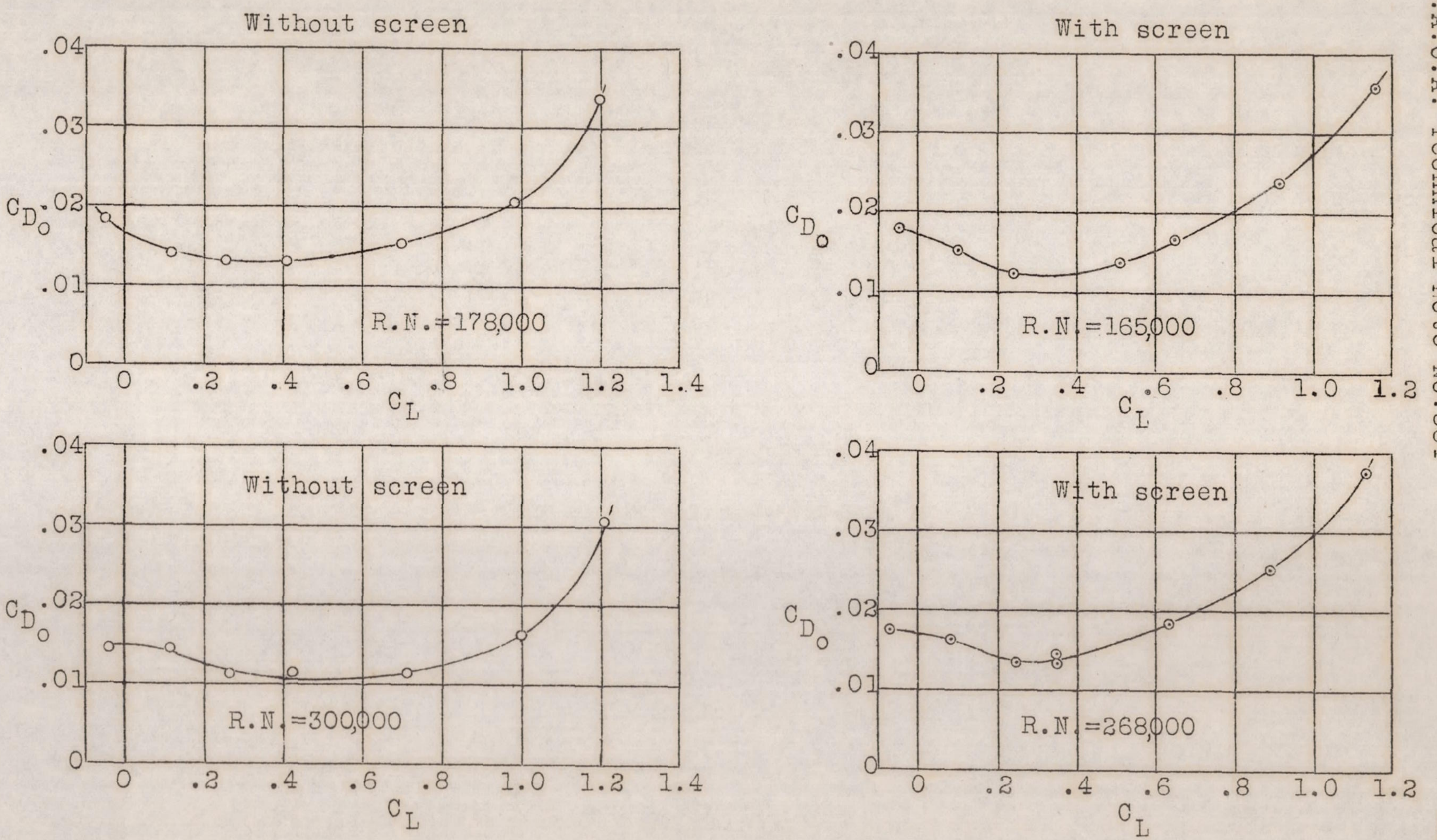


Fig. 12a Scale and turbulence effects on airfoil drag, Clark-Y airfoil.

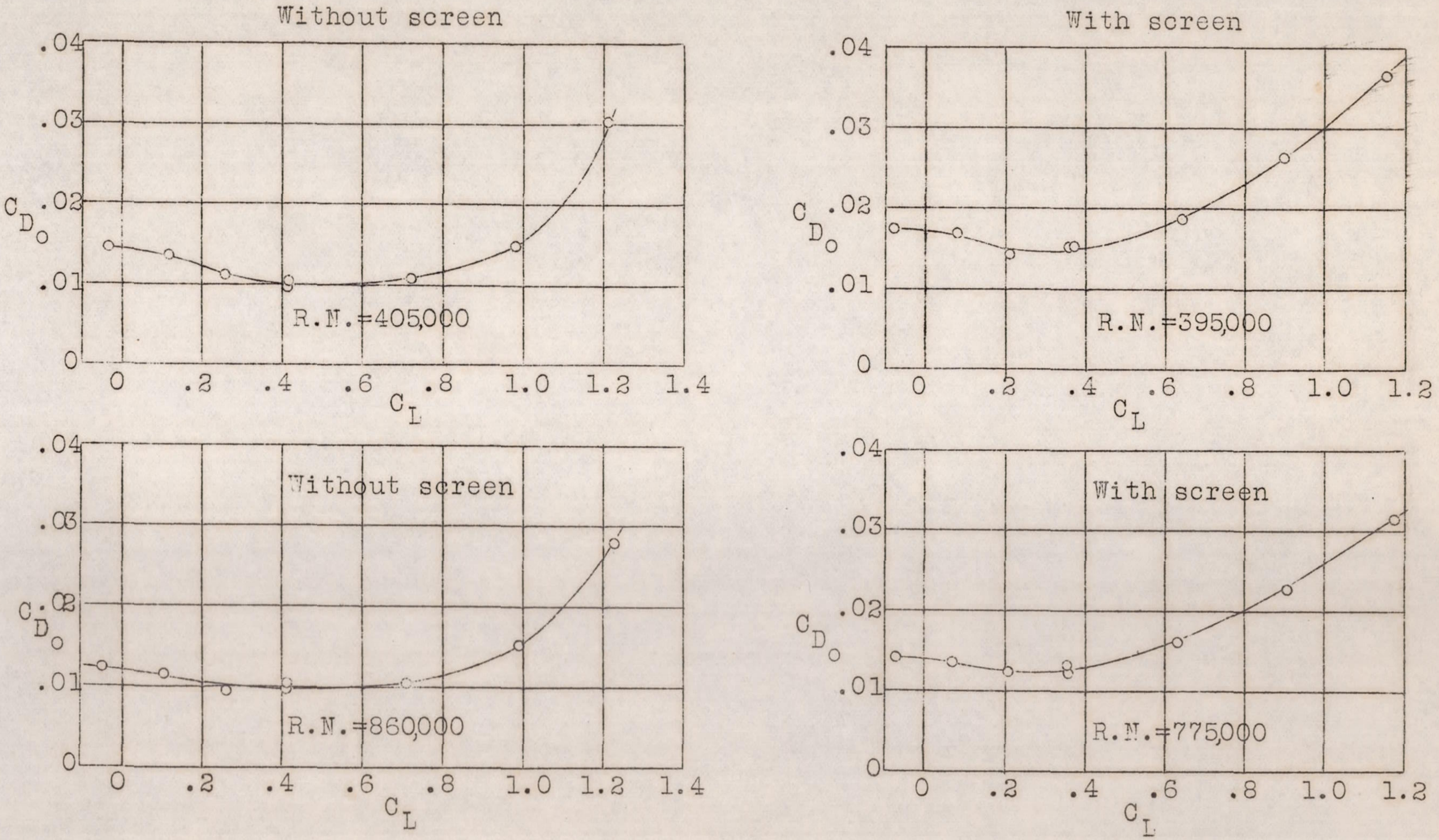


Fig. 12b Scale and turbulence effects on airfoil drag, Clark-Y airfoil.

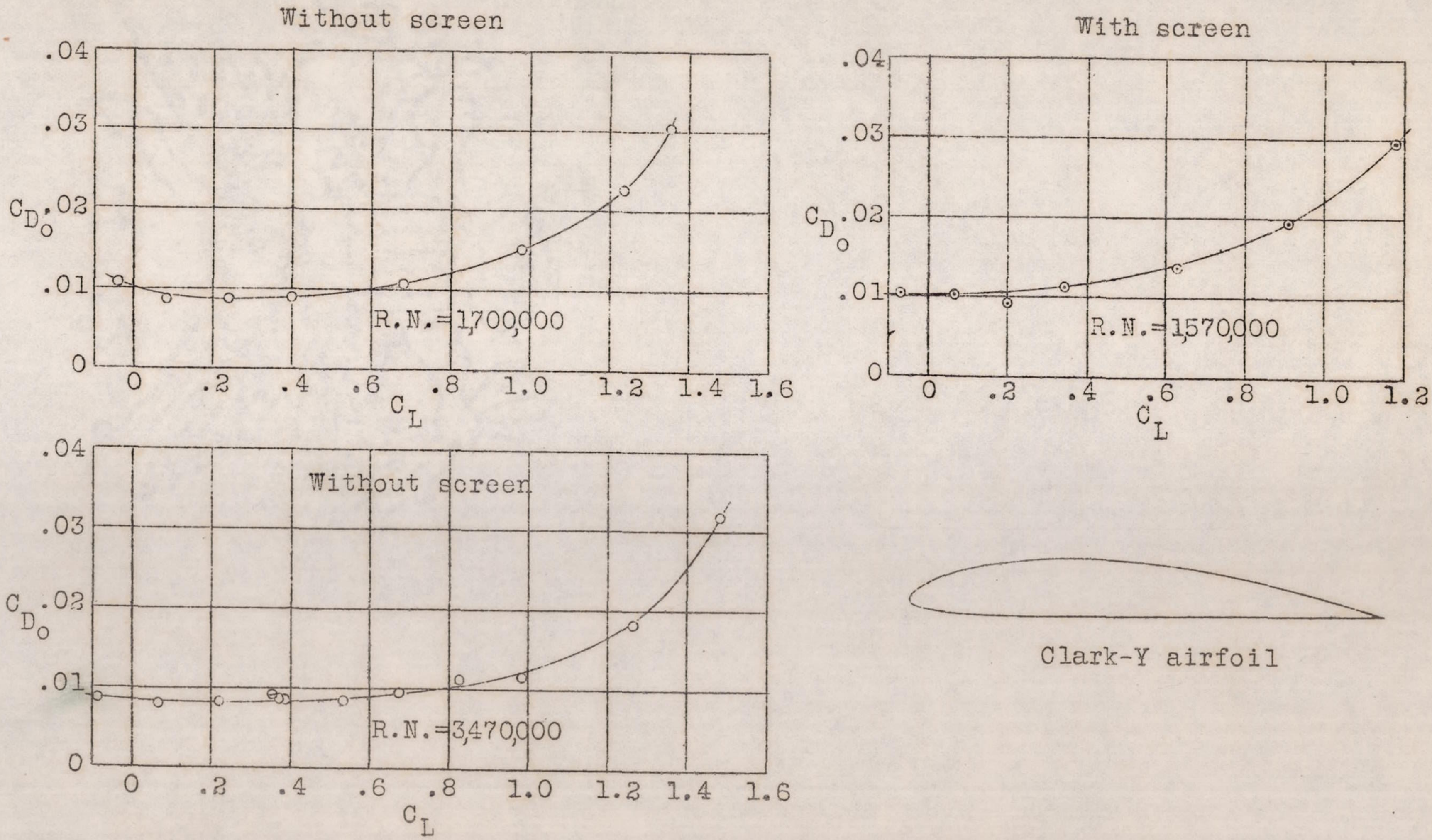


Fig. 12c Scale and turbulence effects on airfoil drag, Clark-Y airfoil